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REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM	
1. REPORT NUMBER Technical Report No. 321	2. GOVT ACCESSION NO. AD -AC95 905	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Description of VERKSAM, the Swedish Vulnerability Assessment Methodology for use with Stationary or Slow-Moving Land or Sea Surface Targets (Volume I)		5. TYPE OF REPORT & PERIOD COVERED Final, Nov — Dec 1979
		6. PERFORMING ORG. REPORT NUMBER SwRI Report 02-5649-001
7. AUTHOR(s) Tom Gyllenspetz		8. CONTRACT OR GRANT NUMBER(s) DAAK11-79-C-0059
9. PERFORMING ORGANIZATION NAME AND ADDRESS Southwest Research Institute 6220 Culebra Road San Antonio, Texas 78284		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DA Project No. 1R665706M541
11. CONTROLLING OFFICE NAME AND ADDRESS DRXSY-LM U.S. Army Materiel Systems Analysis Activity Aberdeen Proving Ground, Maryland 21005		12. REPORT DATE December 31, 1979
		13. NUMBER OF PAGES 61
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) US Army Materiel Development & Readiness Comd 5001 Eisenhower Avenue Alexandria, VA 22333		15. SECURITY CLASS (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

VERKSAM, vulnerability analysis methodology, Sweden, stationary or slow-moving targets, translation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is a translation of two reports from the Swedish National Defense Research Institute (Forsvarets Forskningsanstalt - FOA). The report describes the model behind the computer programs VERKSAM and gives an example of how it has been used. The model is intended for calculation of the effects of conventional weapon systems on stationary or slow-moving targets. The results are the effects in the different functional systems measured by the probability that they are in different conditions after an attack.
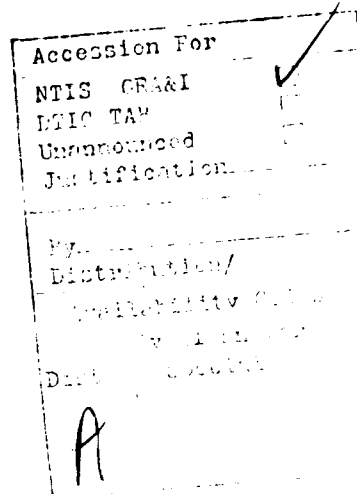
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FOREWORD

This document is basically a translation of FOA Report A 20002-D8 with clarifications by the translator and examples from FOA Report C 1484-D8. Where the text of FOA Report A 20002-D8 does not represent current practice in Sweden, the translator has described such current practice in this document. This work was performed at Southwest Research Institute under Contract DAAK11-79-C-0059 from the U. S. Army Materiel Systems Analysis Activity, Aberdeen Proving Ground, Maryland.

The personnel who assisted in this effort are:

Mr. Patrick H. Zabel, SwRI, who edited the English text and helped in clarifying the practices described;

Mr. Magnus Hagwall, FOA, who advised in current practices and planned future improvements in the use of this methodology in Sweden;

Mrs. Ingrid M. Gyllenspetz, FOA, who advised in the descriptions of assumptions used at FOA;

Dr. Wilfred E. Ba. and Mr. Ernest P. Bergmann, SwRI, who reviewed this document;

Mrs. Sue Lindsay, SwRI, who typed the text; and

Mr. Victor J. Hernandez, SwRI, who prepared the illustrations.

The technical monitor for this effort was Dr. Benjamin E. Cummings, AMSAA.

1. INTRODUCTION

1.1 GENERAL

This report is basically a translation of two reports from the Swedish National Defense Research Institute (Foersvarets Forskningsanstalt - FOA) Stockholm. It is not a straight translation but rather a new report built on the chapters of the originals. Some pieces have been added or changed and reformulated. The content is basically the same as in the main report (Neider - 74, A 20002-D8) [1] but has been changed so that the original Chapter 5 has been included in other chapters and Chapter 6 in this report is basically report C 1484-D8 of A. Fischer - 72 [2].

The report describes the model behind the computer programs named VERKSAM and gives an example on how it has been used.

1.2 TERMS USED IN THE REPORT

Shielding - The thickness of the shield around a critical volume that has to be penetrated if the volume is to be considered damaged.

AFB - Air Force Base

Functional Systems - The systems of the target that are constructed of the critical components, i.e., possibility to steer the ship or radar systems.

Imaginary Volume - Volumes used by the target describer to structure the description into target types.

Solid Angle - The ratio between the area of the unit sphere and the area of a radially projected figure on a unit sphere, the center of which is at the burst point (steradian).

Damage Criteria - The probability, specified by the target describer, that a functional system is influenced if the corresponding critical volume is damaged.

Fragment Zone - The volume between two cones defining the limits of a homogeneous set of fragments.

Critical Volume - A volume that has a function and can be damaged.

Critical Component - A part of a critical volume that corresponds to a certain functional system. Compare damage criteria

Target Types - A set of real volumes surrounded by one or more imaginary volumes all specified on the coordinate system of the target type.

Representation Lines - A line from the burst point to the middle of the distance cut out by the fragment zone on the axis of the cylinder.

2. THE MEANING OF THE MODEL

The model is intended for calculation of the effect of weapon systems upon slow, complex targets. A slow target is one the velocity of which is negligible compared to fragment and warhead velocities. A complex target means that the model will allow a detailed description of the different parts of the target, especially for vulnerability and protection against fragments and warheads; and, whose parts can easily be integrated into a large system describing a target.

The results are the effects in the different functional systems, measured by the probability that they are in different conditions after an attack.

2.1 BACKGROUND

The model is a combination of old models and computer programs, which were used on the IBM-7090. When the 7090 computer was replaced in 1968, the work on this model, called VERKSAM, was started. The aim was stated to be "effects in slow complex targets", this to exclude aircraft and troops. The reason was that aircraft have a great velocity which cannot be ignored, and troops have no significant retardation power making the calculations fairly simple. The model is thus a replacement for several old models calculating effects in ground and sea targets. The model consists of a few independent modules that can be used separately or in combinations to cover different needs of the users.

2.2 THE CONSTRUCTION OF THE MODEL

The calculations are made in four phases that can be worked sequentially or individually. (See Figure 1, Columns 2 and 3)

(1) Burst point generation: At the simulation of one attack, the burst points of the individual warheads are calculated together with their attitude.

(2) Direct and Close Range Effects: Here the program calculates which critical volumes are killed as a consequence of direct hits or a combination of shockwave and intensive fragment impact effects from a close burst.

(3) Fragment Effects: For a given burst point, the probability of kill is calculated for each fragment-sensitive critical component.

(4) Effect in Functional Systems: Through a synthesis of the effects in the individual critical components, the probability that the functional systems are in different conditions is calculated.

The report shows several alternative methods for the different phases of calculations. To each phase there is or will be computer programs for the different alternatives. The programs are stored in a library with the name VERKSAM at FOA.

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INPUT   CALCULATION   OUTPUT (Same as input
                                                          to next phase)

```
┌──────────┐          ┌──────────────┐          ┌──────────────┐
│ Tactics  │══╗       │ Burst Point  │══╗       │ Burst Point  │
└──────────┘  ╚══════▶│ Generation   │  ╚══════▶│ Coordinates  │
Phase 1               │              │          │              │
┌──────────┐  ╔══════▶│              │          └──────────────┘
│ Real     │══╝       └──────┬───────┘
│ Volume   │                 ║
└──────────┘                 ▼

┌──────────┐          ┌──────────────┐          ┌──────────────┐
│ Direct and│         │ Direct and   │══╗       │ Killed Critical│
│ Close Range│═══════▶│ Close Range  │  ╚══════▶│ Components    │
Phase 2 │ Effect   │         │ Effects      │          │              │
└──────────┘          └──────┬───────┘          └──────────────┘
                             ║
                             ▼
┌──────────┐          ┌──────────────┐          ┌──────────────┐
│ Real     │══╗       │              │══╗       │ Kill Probability│
│ Volume   │  ╚══════▶│              │  ╚══════▶│ for each     │
└──────────┘          │ Fragment     │          │ Critical     │
┌──────────┐  ═══════▶│ Effects      │          │ Component    │
Phase 3 │ Critical │         │              │          │              │
│ Volume   │  ═══════▶│              │          └──────────────┘
└──────────┘          └──────┬───────┘
┌──────────┐  ╔══════▶       ║
│ Fragment │══╝              ▼
│ System   │
└──────────┘          ┌──────────────┐          ┌──────────────┐
                      │ Effect in    │══╗       │ Probability that a│
┌──────────┐          │ Functional   │  ╚══════▶│ Functional System│
│ Functional│═══════▶ │ Systems      │          │ has a Certain │
Phase 4 │ System   │         │              │          │ Condition     │
└──────────┘          └──────────────┘          └──────────────┘
```

Figure 1. Flowchart for Calculations

2.3 INPUT TO THE MODEL

The input to the four phases of calculations can be divided into six groups, of which the three first can be said to be the target description. The six groups are:

(1) Real Volume Description: Gives geometrical data and materials for all volumes with capacity to retard fragments/warheads. This part is called the external target description.

(2) Critical Component Description: Gives the vulnerability data for the fragment-sensitive components. This part is called the internal target description.

(3) Functional System Description: Defines how effects to the critical components influences the conditions of different functions of the target.

(4) Direct and Close-Range Effects: Gives volumes which surround critical components which are killed when a burst occurs inside the volume. The sizes of the volumes depend on the effect of the warhead at different distances, on the critical components vulnerability, and on the location of the components.

(5) Fragment Data: Gives the distribution of the classes of masses of the fragments, velocities and number of fragments in each fragment zone. (Conventional Warhead)

(6) Tactical Data: Consists of certain data for the attack such as point of aim, point of drop, and description of the individual warheads until the time of the burst. In the description, the variation of different parameters, i.e., systems variations, ballistical variations and variations of fuzes, can be defined.

3. DESCRIPTION OF INPUT

3.1 TARGET DESCRIPTION AND GEOMETRY

The target is described by a number of volumes with each having one of the following three characteristics; vulnerability, protection or aid to the calculations. They are called respectively <u>critical</u>, <u>real</u> or <u>imaginary</u> volumes. All volumes are convex (that is all corners will for some viewpoint be on the edge.)

A <u>critical volume</u> is defined as vulnerable to fragments, such that if the volume is damaged one or more functions of the target are influenced. The part of the critical volume which, when damaged, influences a given function is called a critical component. Each component has a damage criterion (see 3.1.2).

The vulnerability of the critical volumes to fragment impacts is described by a <u>shielding</u> factor. For the fragment vulnerability calculations, two alternative methods are given which use different critical volume description techniques:

(1) The critical volume is described as a cylinder without retardation capability. The parameters of the cylinder are defined by the real critical component's shape and volume.

(2) The critical volume is described as a real volume that has critical spaces on its surfaces.

A <u>real volume</u> describes a real volume's capability to retard a fragment or warhead.

An <u>imaginary volume</u> has only a geometrical description that is used to simplify the geometrical description of a target, and is used to optimize the speed of the calculations (see 3.1.1 and 4.5).

In the type of volumes which can be killed by direct and close range effects, some real volumes are included (as well as all critical volumes). Those real volumes are vulnerable to direct and close range effects but not to fragments.

A logical, physical and functional group of volumes is called a <u>target-type</u>. The geometrical description in one target-type is based on a coordinate system specific for this target-type. The target-type is surrounded by a convex, imaginary volume. Examples of target-types are an aircraft, a part of a ship or a hill in a forest.

A complex target is described by a number of target-types defined in the complex target's own coordinate system. One target-type can be used in many places in the complex target, for example, if the complex target is an airbase the target-types could be aircraft.

The critical volume description for one target-type consists only of critical volumes while the real-volume description consists of both real and imaginary volumes.

The walls of the volumes can be described by giving the corresponding surfaces a thickness and a retardation factor. A volume's power to retard a fragment is measured in meters of retarding material per meter. As material, the most common material in the target is chosen. The other materials used, have to be converted to this unit material. A retarding power of B meter dural* per meter means that a fragment that goes through a volume, loses for each meter in the volume, the same amount of penetration capability as if it had gone through B meter of dural. To this the retardation in the walls has to be added (calculated the same way as inside the volume, see Figure 2.)

3.1.1 Real Volume Description

The real volume---the external target---description describes the capability of the target to retard fragments and projectiles. The description consists of real volumes and imaginary volumes. In certain cases, a real volume can have critical attributes as vulnerability and influences on different functions. The description is used when generating the burst points and calculating fragment retardation. A real volume is a convex volume within which equal retardation of fragments and projectiles is assumed. Valid geometrical shapes for real volumes are: convex polyhedron, cylinders, spheres and truncated portions thereof. The convex polyhedron can have an arbitrary number of surfaces, but to minimize the calculations it should be described as a parallelepiped preferably with right angles or with the edges parallel to the coordinate axes. The latter are called boxes.

A logical or physical group of volumes makes a target-type, i.e., an aircraft or a network of pipelines. The real volumes of one target-type are in a hierarchy where any two volumes either are completely separated or one of them is surrounded by the other. As an aid to increase the hierarchy dividing, and thus optimize calculation time, the target description can use one or more imaginary volumes. Those are described in the same manner as real volumes but do not have any protective retardation capability. An imaginary volume can only be surrounded by another imaginary volume but can have many levels of real volumes inside itself. An example of the construction of a target is shown in Figure 3.

Certain real volumes have to be treated separately; such as with the description of forests and water. Forests are assumed to consist of volumes with non-homogeneous masses where the retardation changes between nil and total retardation [3]. At the burst point generation, the burst in a forest is determined by a distribution function. This is a distribution function over distance traveled in a certain kind of forest for a certain warhead. At the fragment effect calculation, the retardation in a forest is substituted with a distribution function over the reduction in number of effective fragments, depending on the height and length of the fragment trajectories. The

---

* "Dural" is used as a generic term for aluminum. Ballistic penetration tests in Sweden are conducted using an alloy, SIS 4338.06, which is similar to Al 2014 T6.
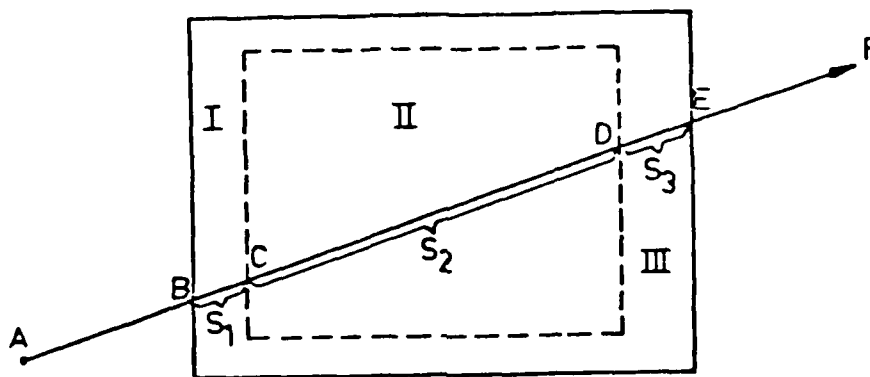
Fragment that travels along the line AF loses the penetration capability "VAG" from point B to E

$$VAG = S_1 \cdot M_1 + S_2 \cdot M_2 + S_3 \cdot M_3 \qquad (1)$$

Where M_i = retardation power in a wall (or the inside of the volume, ($i=2$))

The dotted lines depict the inner side of the walls, S_i = distance the fragment travels.

Figure 2. Fragment Retardation in Real Volumes

burst point generation against water gives detonation under the water surface without fragment effects. Any close range effects are treated separately.
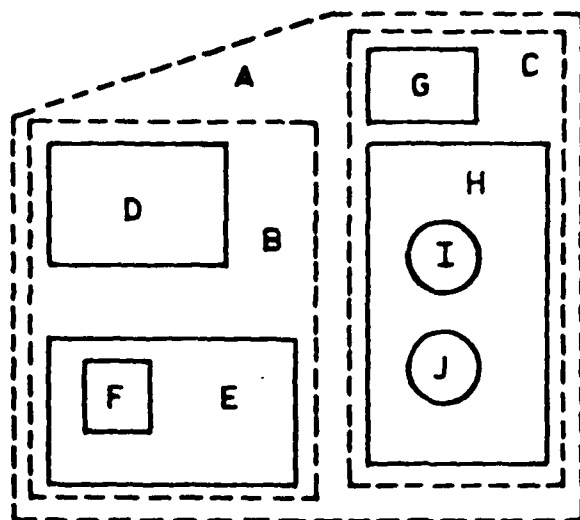

```
-----  imaginary volumes:  A, B, C
_____  real volumes:   D, F, E, G, H, I, J
```

Figure 3. The External Target Description of One Target Type

3.1.2 Critical Volume Description

The critical volume description, also called the internal target description, describes the fragment-sensitive components, their vulnerability measured in thickness of shielding, and vulnerable space and damage-criteria including any other functions which influence the target. The geometrical description consists of convex critical volumes which have a shield. The shield describes the vital components vulnerability to fragments, measured in meters of material, where the material is the unit material used for the target (see 3.1.1), mild steel or dural. A vulnerability of one meter of mild steel means that a fragment must have a weight and velocity enough to penetrate one meter of steel to have any possibility to kill the critical component. The critical volume is divided in one or more critical components

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which have their own damage criteria. A damage criterion is the probability
that a certain function is influenced when an effective fragment penetrates
the critical volume. An effective fragment shall at impact have a penetra-
tion capability which is greater than the shielding of the volume. Two al-
ternative methods for calculation of fragment effects are shown below. Dif-
ferent methods are used for these critical volume descriptions.

3.1.2.1 Critical Volume Described as Cylinders

This method is a further development of the method to describe criti-
cal component with lines. (Nomark 1968) [4]

Each critical volume is approximated with a cylinder. The projected
surface of the cylinder from different angles should approximate the surfaces
of the real critical volume. The position of the critical volume is indepen-
dent of the real volume description, but has to fit so that the retardation
of fragments is calculated in a satisfactory way. The fragment retardation
is calculated by using the real volume description up to the point where the
trajectory of a fragment hits the surface of a cylinder (critical volume).
This affects the choice of shield, which depends on the angle between the
trajectory and the cylinder. Discussion about the construction of cylinders
can be found in Section 4.3.4.3.

3.1.2.2 Critical Volumes Described as Polyhedra with Critical Surfaces

This method replaces the simulation method described in Hagwall-67.[5]

The real volume description which has critical components is treated
as follows. On the surfaces of the volume, a number of critical surfaces are
defined. They are given attributes such as shielding, damage criteria, and
scalar area. The fragment effects are calculated for the mid-point of the
surface, which influences the choice of the direction-independent shielding.
(This shielding is termed "direction-independent" since its normal thickness
is always used rather than the thickness along the trajectory.)

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3.1.3   Functional System Description

For each functional system, the critical components which affect the function are specified. Two models are used; they are intended for different applications. The models have, among other differences, different input requirements.

Model 1: Synthesis of effects in systems of the type; aircraft on an airbase where the conditions of interest for each system are:

   (1)   The system is unusable for a certain time or longer.

   (2)   The system is usable to some extent directly after the attack.

The input consists of a number of testing and repair time estimators plus a description of which components the functional system consists and how they are functionally interrelated.

Each vulnerable part has a repair or exchange time, a test and control time plus a note on which vulnerable parts are repaired and/or tested concurrently. For the complete system, the following times have to be added: time for malfunction diagnosis, time for transportation to the repair site, time for delivery of spare parts and items. The conditions describe whether or not the system is still functional T hours after the attack. The influence of different components on the function can be assessed by ignoring damages to other components of the functional system.

Model 2 is used for synthesis of effects in a functionally interrelated chain of technical and tactical systems in, for example, a ship where the construction of the functional system gives dependencies on different condition levels. The interacting conditions describe whether a functional system is killed or not during an attack.

The input defines the different subsystems which are used in a hierarchy to define the critical technical systems of the target; that is, those systems necessary for the craft to move (the engine), to maneuver (rudder or steering system), etc. Tactical systems are constructed of the different technical systems. The critical components are in the lowest level of this hierarchy.

The construction of the functional systems is described by defining which subsystems and/or critical components are parts of the system, plus their relationship in "and/or" chains.

The tactical systems are built from technical systems which are dependent. One component can be in more than one functional system; parts of the electrical system, for example, can be in many different functional systems. Effects in the tactical systems thus cannot be calculated directly from the effects in the technical systems, but has to be calculated in a special model (called VERANA) which uses Monte Carlo simulation (Andersson 1974). [6]

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3.2 DIRECT AND CLOSE RANGE EFFECT DATA

For the close range effects calculations, a special target description consisting of convex volumes is used. For each of these volumes, the critical components which are killed by a burst inside the volume, are defined. The blast and fragment effects of such a burst are considered to be enough to kill completely the critical components inside the specified volume. The volumes surrounding the critical volume have no shielding power and this surrounding-volume size depends on the combination of target and warhead.

3.3 FRAGMENT DATA

Fragment data are used only for fragment effects calculations. An HE projectile has the shape and construction shown in Figure 4. In the figure, the casing and the explosives are shown schematically.
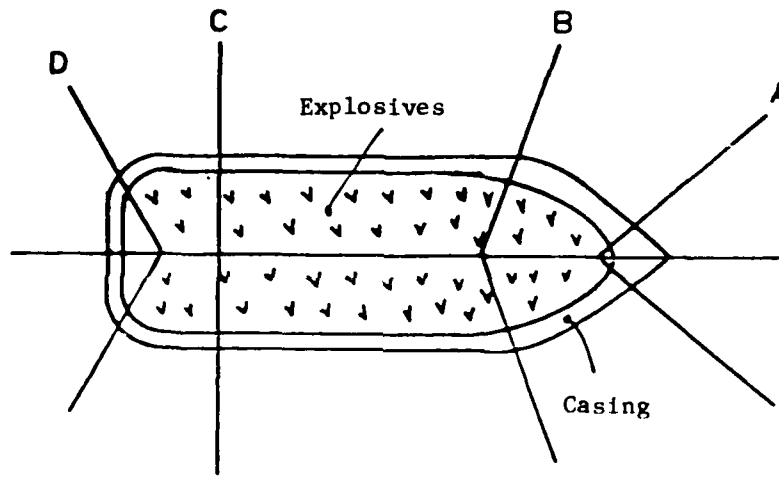
A, B, C and D are cones which limit fragment distribution zones.

Figure 4.   Schematic Figure of an H.E. Warhead

When the warhead detonates, the casing ruptures into different size fragments which are thrown in different directions and with different velocities. As the warhead is axisymmetric (viewed from the tip), the fragments are thrown with radial symmetry. In most cases, the warhead has a forward velocity, which has to be added vectorially to the velocity of the fragments due to the detonation. This gives a certain initial velocity and

direction for fragments coming from a certain zone of the casing. In the
different fragment zones, the total number of fragments and the distribu-
tion in sizes are different. In Figure 4, the lines A, B, C and D are
examples of limits between such zones. The limits thus have the shape of
cones with the tip on the longitudinal axis of the warhead. For the de-
scription of the warhead, the spray of fragments is divided into a number
of fragment zones. A fragment zone can contain no fragments if appropriate.
In each fragment zone, the fragments are assumed to be thrown uniformly
and from one point on the longitudinal axis of the warhead. The limits be-
tween fragment zones are chosen so that characteristics (i.e., fragment
types, size distribution and velocities) may be assumed uniform within each
zone so defined. The initial velocities of the fragments are assumed to vary
linearly between the cone limits.

Input to the calculations should describe the fragment data at the time
of the burst. Fragment data are often determined by experiments with a static
warhead. In the calculations, the velocity of the warhead has to be added
vectorially to the velocity of the fragments at the limits of the cones. (See
Figure 5) Thus, we get a new set of cones with different cone half angles.
It is possible for the resulting fragment zones to overlap. This must be
avoided by constructing new fragment zones of the overlapping zones.

Effects from the position of the burst point (see burst point genera-
tion), such as difference thicknesses of the casing, have to be considered
in inputting the fragment data. Division into fragment types depends on
material, shape and size.

Controlled fragmentation produces fragments with a given shape and size
at the burst. The mass of fragments from non-controlled fragmentation varies
and is determined experimentally as a distribution. The shape of the frag-
ments can be determined theoretically. Shape and material determines the
drag coefficient and the penetration coefficient for a given material of the
target.

3.4   TACTICAL DATA

Tactical data are used only at burst point generation. The methods for
calculations are intended for attacks with conventional weapon systems where
the elevation angles of the warheads are considerably far away from 0 degrees.
Primarily, the calculations are intended for airborne systems, as attack air-
craft or ground-to-air missiles, but also high trajectory artillery can be
treated by the program.

Tactical data are considered to be partly data on the quantity of the
stowed munitions and the tactics used and partly data on the fuzes of the war-
heads. The burst point generation is made by simulation using Monte Carlo
methods. Much of the tactical data are expressed as means and deviations for
the delivery parameters, range and deflection.

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Limits of the
Fragment Zones
for a static warhead.

Limits when the
Velocity of the
Warhead is added.

New Fragment Zone, Created by
Two Intersecting Zones.
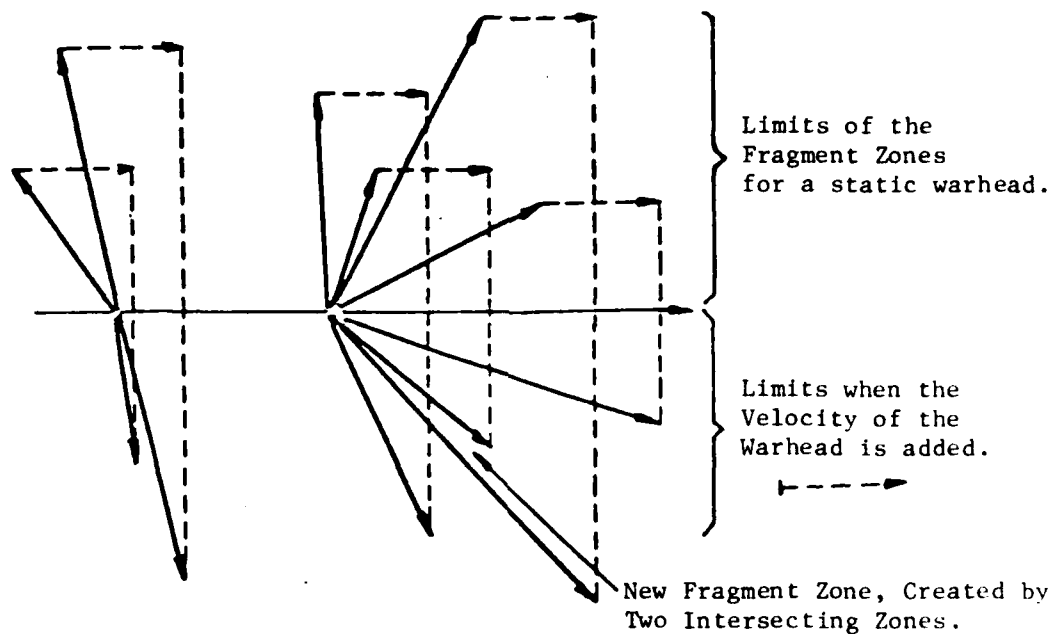
The vectors show the velocity of the fragments in the fragment zones
and in the limits. The vectors above the axis shows velocities for a static
warhead and below for a moving warhead. The dotted vertical lines shows the
velocity of the warhead and the remaining dotted lines illustrate the vector
addition.

Figure 5. Vectoring Fragment Initial Velocity

Weapons Load consists of number of weapons per attack plus the ideal pattern for the burst points, for example, with the drop of bombs or cluster bomb units.

The delivery tactics of the weapon system consists of choice of aiming point and delivery point plus the behavior of the warhead in the trajectory; for example, the oscillations if dropped by a parachute.

The attitude is the direction of the longitudional axis of the warhead. Deviations connected to the data above are defined as deviations to the choice of drop point, aiming point, system errors plus variances normal to exterior ballistics.

Fuze data consists of type of fuze, probability for functioning properly, sensitivity to and behavior upon ricochet and the point of burst as compared to point of impact. Fuzes used are: contact, delay and proximity.

4.   DETAILED DESCRIPTION OF ALGORITHMS

4.1   BURST POINT GENERATION

Burst point generation determines whether the warhead has detonated or not at a simulated attack. If a detonation occurs, the following parameters are calculated: burst point location, attitude of the warhead, and in what target type and volume the burst occurs. The calculations are made in two phases. By using data on munition, aiming precision and delivery tactics for each weapon, the position and heading of the weapon are determined in an area around the target (trajectory generation). The intersections between the trajectory and the real volumes of the target are determined, then taking into consideration the type of fuzes, the burst point location is calculated (burst point determination), Figure 6.

INPUT   CALCULATIONS   RESULT

```
                          ┌──────────────┐
                          │ Random       │
                          │ Number       │
                          │ Generator    │
                          └──────────────┘
                                 ⇕
┌──────────────┐          ┌──────────────┐        ┌──────────────────┐
│ Tactical     │═════════▶│ Burst Point  │═══════▶│ Burst Point and  │
│ Data         │          │ Generation   │        │ Attitude for each│
└──────────────┘          └──────────────┘        │ Warhead, plus    │
                                 ⇕                 │ Real Volume in   │
                          ┌──────────────┐         │ Which            │
┌──────────────┐          │ Intersections│         │ the Detonation   │
│ Real         │═════════▶│ Between      │         │ Occurs           │
│ Volume       │          │ Trajectories │         └──────────────────┘
│ Description  │          │ and          │
└──────────────┘          │ Real Volumes │
                          └──────────────┘
```
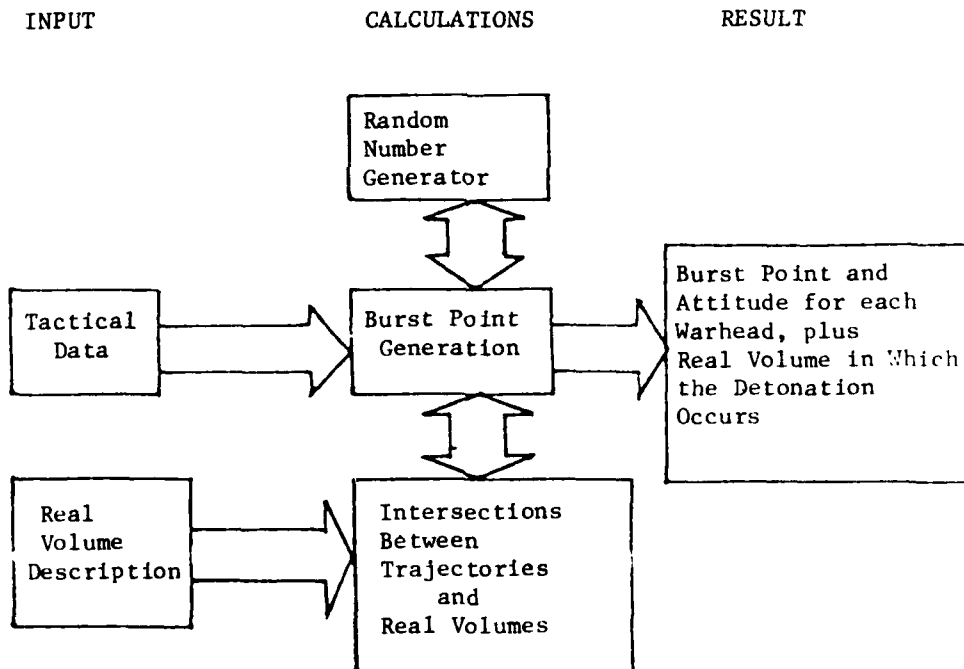
Figure 6. Flowchart for Burst Point Generation

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4.1.1 Trajectory Generation

Alternative attack methods which can be used in the program are:

(a) Use of rockets or missiles, individually or in salvos.

(b) Drop of bombs at specified time intervals from a horizontal straight course.

(c) Drop of one or more cluster bombs with the bomblets in a given pattern.

The trajectory simulation is assumed to start from a point above the target. The calculations, as shown in Figure 7, are separated into three phases.

4.1.1.1 Phase 1 - Starting Conditions

To determine randomly the point of fire, the starting point of the warheads was in a horizontal plane at the same attitude as the weapon carrier plus the mean trajectory of the warheads. The direction of the attack is determined by randomization over a rectangular distribution, with the desired direction as mean. When delivering rockets in a dive, the point of fire is determined given the direction and distance to the aim point. The mean trajectory (for all warheads) that is randomized with a normal distribution around the aim point will also incorporate system and aiming errors.

When bombing from a high altitude from level flight, the release point is randomized in a horizontal plane by normal distributions (width and length). Here the aiming error contributes. This plane (the drop plane) is at randomized altitude above the target, again using a normal distribution but above a minimum altitude. In the drop plane, the individual warheads are positioned in a given pattern. The mean trajectory for the warheads determined by a normal distribution, with a specified drop angle as mean, includes errors in the weapons system.

When the drop of more than one cluster bomb is made, they are simulated as separate weapons carrier where the point of drop is randomized over a plane (horizontal) with width and length (as a normal distribution) along the heading. In this plane, the ideal points of hit are distributed evenly along the heading and ideal points of hit for the bomblets are distributed according to a given pattern.

4.1.1.2 Phase 2 - Simulate the Position of the Warheads in a Horizontal Plane Through the Target

The trajectories of the individual warheads are randomized, using a normal distribution about mean trajectory. The end of the trajectory is approximated with a straight line which touches the real trajectory in one point within the area where the impacts can be expected. The trajectory is determined by adding a correction (input), attitude change, to the elevation angle
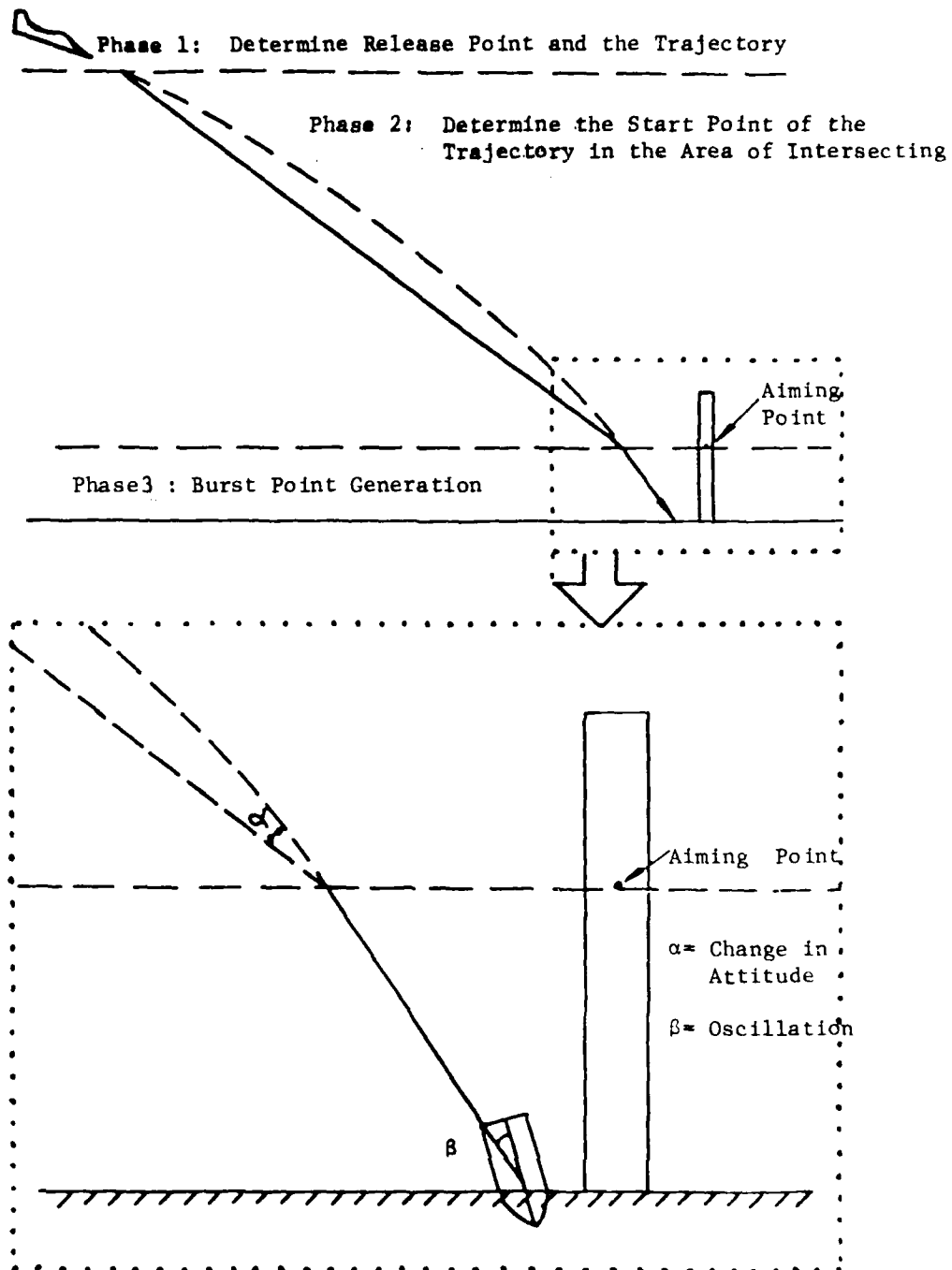
Figure 7. How to Determine the Trajectory

of the ideal trajectory. Consideration is also taken to the attitude of the warhead in the trajectory caused by, *for example, oscillations.* (*Might be caused by the parachute.*)

4.1.1.3 Phase 3 – Determine the Burst Point Along the Trajectory

The burst point represents the location of the projectile when the detonation occurs, and is used as a start point for fragment travel. For a superquick (SQ)-fuzed projectile, the burst point is assumed to be at the surface of the target. For a delay-fuzed projectile, the burst point is assumed to be a distance, S, farther along the trajectory; where this distance is equal to the product of the fuze delay time, t, and the projectile impact velocity, V_I. See Figure 8.

| The Tip Hits a Surface | Burst Point Assumed With a SQ-Fuzed Projectile | The Burst Location Assumed With a Delay-Fuzed Projectile |
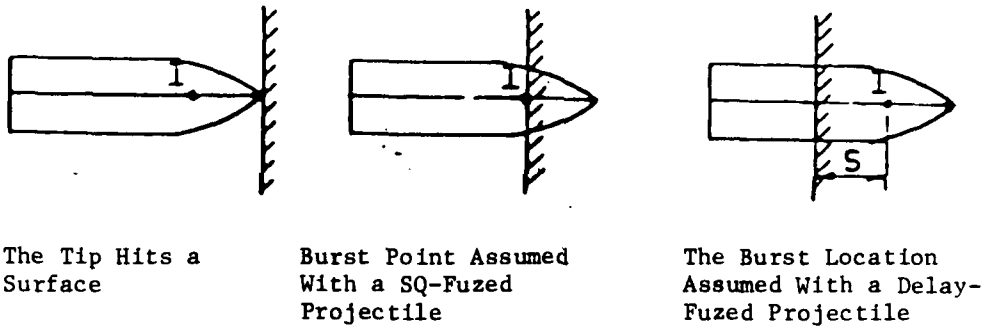
I = Burst point (for a superquick-fuzed projectile).

S = The distance the projectile travels while the fuze delay operates.

Figure 8. The Burst Point

Forests are treated differently from other volumes. *The distance the warhead travels through a forest before the fuze is initiated is determined by a distribution function which depends on the type of forest and elevation angle.*

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4.1.2 Burst Point Determination for Different Fuzes

The program can handle contact fuzes, with or without delay, and proximity fuzes. For the first type of fuze malfunction treated, the warhead is a dud. If a proximity fuze fails to function properly, the warhead is treated as having a superquick, contact fuze. All types of warheads can change direction at the impact, depending on the angle of impact.

By using the mass velocity, and penetration coefficient of the warhead, the point where the warhead stops in the target is calculated. For superquick (SQ) contact fuzes (without delay), the fuze is initiated when the trajectory intercepts the first real volume with a surface having a thickness not zero and where the angle of impact is not too shallow for the fuze to initiate. And for a delay-fuzed projectile, the warhead detonates after a farther distance (see Figure 8). This distance is given in the fragment data and depends on the retardation power of the target volumes, the velocity of the warhead at the target and the time from the initiation of the fuze to the detonation. For fuzes with delay, this time is adjusted on the fuze and the fuze delay time input. For SQ fuzes (without delay), it depends on the sensitivity of the fuze.

The critical volume into which the warhead penetrates during the delay of the fuze is considered to be killed. (Section 4.2) If a warhead with delay hits the water surface and does not initiate the fuze while ricocheting, a miss is considered.

Changes to the trajectory at different angles of attack are indicated on Figure 9. In the input, a number of impact angles are defined; these are the limits between which the warhead changes direction. The new direction is a product of a factor (defined in input) times the angle of impact. The change of direction has an effect on the velocity of the warhead, but this is not considered. The shallower angles, give a ricochet without initiating the fuze, which means no detonation. The next interval of impact angles are those within which the fuze of the warhead initiates as it ricochets resulting in a detonation. For even greater angles, the fuze is initiated and the trajectory is unchanged. At angles close to 90 degrees, the trajectory of the warhead changes towards the perpendicular to the surface of the volume; the fuze also initiates.

Proximity fuze functioning conditions are illustrated on Figure 10. Each volume in the target which might initiate a proximity fuze has a radar reflection coefficient. The height of burst is approximated by a vertical line from the warhead to the surface. The height of proximity fuze initiation over a real volume is a normal random number (gaussian distribution) times the radar reflection coefficient for the volume. Detonation is assumed when the height of the projectile over the surface equals the sum of the component height plus the fuze initiation height. If this condition has not been met prior to the projectile contacting a component or the surface, detonation is assumed at the contact. The sensitivity of the proximity fuze to forests is calculated in a special way, see Reference 3.

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Figure 9. Changes in the Trajectory at Different
Angles of Impact
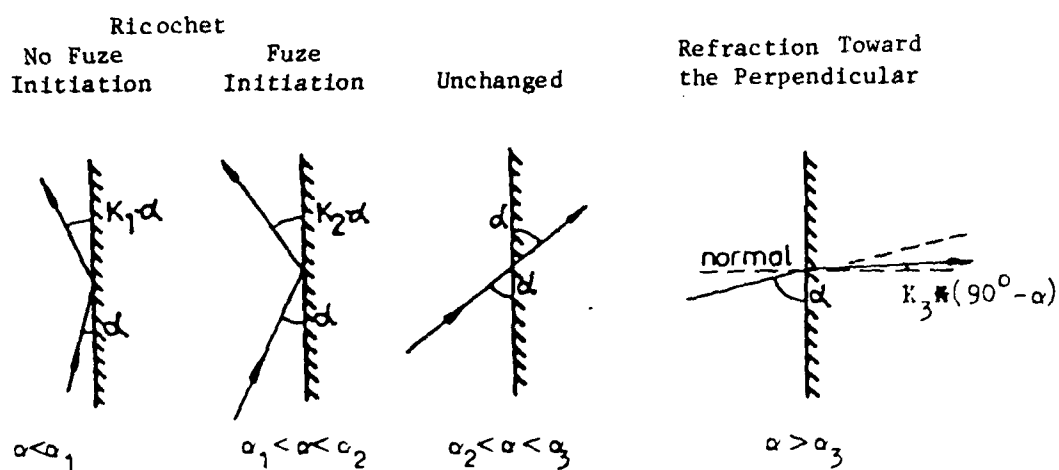
α = Angle of impact

α_i = Limits

K_i = Constants

A = Burst Point for a Fuze Which is Functioning Properly

C = Burst Point for a Fuze Which Fails to Function on the Proximity Feature

z = Randomized Height for the Initiation of the Fuze

r_i = Radar Reflection Coefficient for Real Volume i

$a = z \times r_1$; $b = z \times r_2$; $r_3 = 0$

$q = z \times r_1$

$b = z \times r_2$

Trajectory of the Warhead
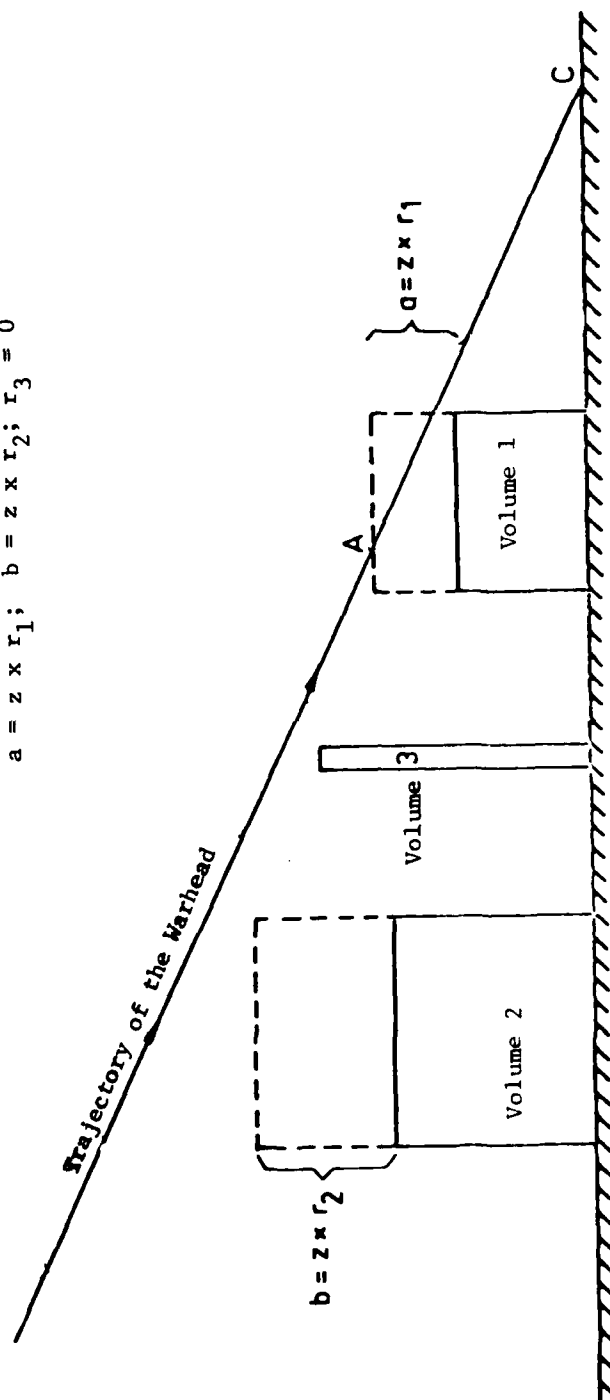
Volume 1

Volume 2

Volume 3

A

C

Figure 10. Burst Point Generation with a Proximity Fuze

4.2 DIRECT AND CLOSE RANGE EFFECTS

Direct effects are kinetic energy penetrator effects of the warhead before the burst. The volumes penetrated by the warhead are considered to be killed.

Close range effects are a combination of blast and fragment effects. For the critical components, there are close range effect volumes, the size of which depends upon the high explosive charge and the target description. A burst inside such a volume will kill all critical components which are inside, partly by close range effects and partly by secondary effects, i.e., a mast that is cut off will have all its critical components assumed non-functional. By computing the close range effects before the lengthy calculations of fragment effects, these latter calculations may be omitted if a close range burst has occured. During penetration and at the burst, the volume of the warhead is assumed zero. This assumption renders the model incapable of computing damage to components through which the projectile would pass prior to detonation unless the trajectory (a line) actually passes through the components. One method which has been used to consider the kinetic energy penetrator effect of the warhead is to make the volumes passed during the fuze delay functioning larger by the radius of the warhead in the direction toward the trajectory and then rerun the computer program. A calculation like that has to be done separately from the fragment effects calculations. These reruns involve temporary modification of the target description.
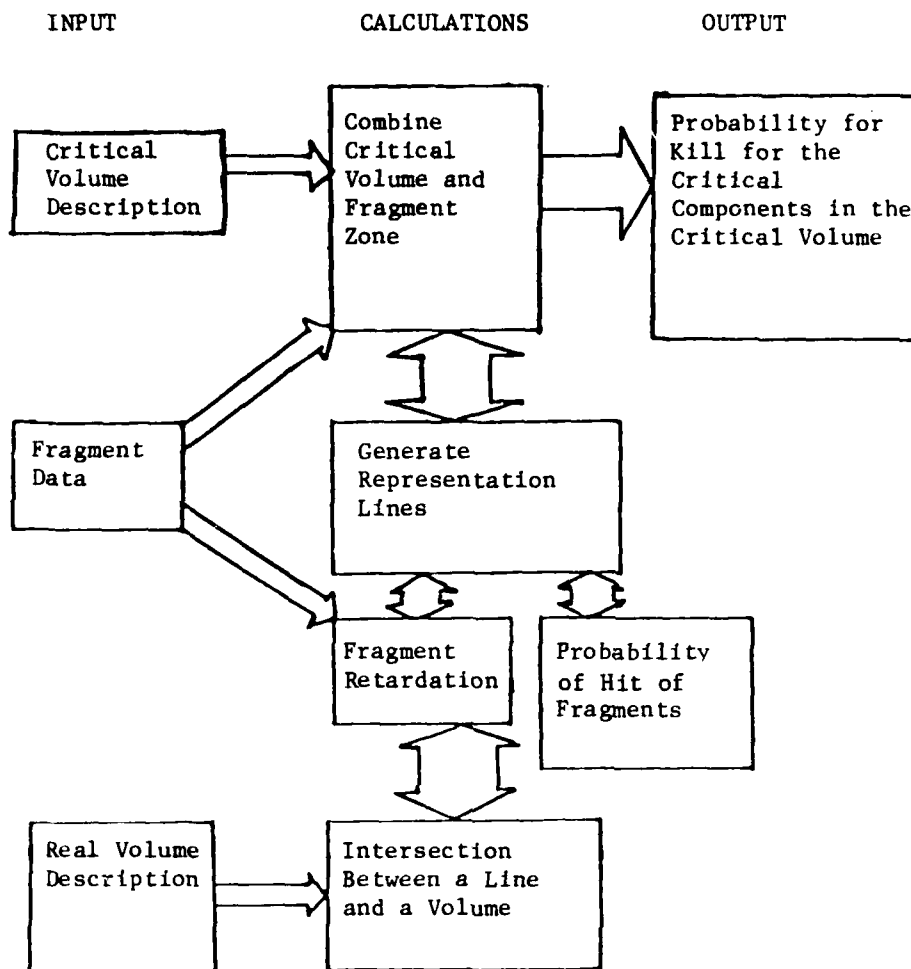
In considering the use of contact fuzes with delay, certain close range effects are added, which can only be calculated at the burst point generations. (See 4.1.2)

4.3 FRAGMENT EFFECTS IN INDIVIDUAL CRITICAL VOLUMES

4.3.1 Principles of Calculations

The calculations are made principally as follows. When a burst occurs, effects in each critical volume are calculated independently of each other as shown on Figure 11. Secondary fragment effects, as for example spall from the holes made by the warhead in volumes, are not considered.

Fragment effects in a critical volume are defined as the probability that at least one effective fragment hits a vulnerable surface in the critical volume. Damage in a critical volume can affect one or more functions of the target. For each function and critical volume, one critical component is defined. Thereby, for each critical volume the probability to kill that part of the function, which the critical component defines, is calculated. If any part of the critical volume is in any of the projectile fragment zones, for each zone so intruded, a number of lines are generated to determine each part of the critical volume which is inside any fragment zone, in any of the different solid angles being considered. (These solid angles represent fragment patterns from the warhead. The apices of the angles are at the burst point. The angle is that of the unit sphere subtended by the fragment zone cones and is described in steradians.) Along each line, called representation line, the retardation (considered to be the mean retardation in that solid angle) is calculated. For each critical component in the volume, "PUT" is calculated. "PUT" is the addition to the probability of kill in the solid angle represented by the representation line.

```
        INPUT              CALCULATIONS              OUTPUT

                          ┌─────────────┐      ┌──────────────────┐
                          │  Combine    │      │ Probability for  │
  ┌──────────────┐        │  Critical   │      │ Kill for the     │
  │ Critical     │───────▷│  Volume and │═════▷│ Critical         │
  │ Volume       │        │  Fragment   │      │ Components in the │
  │ Description  │        │  Zone       │      │ Critical Volume  │
  └──────────────┘        └─────────────┘      └──────────────────┘
                                  ⇕
                          ┌─────────────┐
  ┌──────────────┐        │  Generate   │
  │ Fragment     │═══════▷│ Representation│
  │ Data         │        │  Lines      │
  └──────────────┘        └─────────────┘
                            ⇕         ⇕
                   ┌───────────┐ ┌──────────────┐
                   │ Fragment  │ │ Probability  │
                   │ Retardation│ │ of Hit of    │
                   │           │ │ Fragments    │
                   └───────────┘ └──────────────┘
                            ⇕
  ┌──────────────┐   ┌──────────────┐
  │ Real Volume  │   │ Intersection │
  │ Description  │──▷│ Between a Line│
  │              │   │ and a Volume │
  └──────────────┘   └──────────────┘
```

The problems which have to be solved to compute the fragment effects
in one volume are:

- Generation of representation lines for one fragment.

- Computations for each representation line of the probability that
  a fragment hits the volume in one solid angle.

- Computation of number of effective fragments in the solid angle which
  is represented by the representation line.

To generate representation lines and compute the probability for hits
along the lines, there are two different techniques. In one technique, com-
ponents are described as cylinders, while the other uses polyhedrons to de-
scribe the components.

Figure 11. Flowchart Showing how to Compute the Fragment Effect

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$$PUT = 1 - (1-PSKADA * PTRAFF)^N \qquad (2)$$

where N = number of effective fragments in the fragment zone. (Fragments with a penetration capability greater than the sum of the shield of the critical volume and the retardation along the line.) See Appendix A.

PTRAFF = the probability that an arbitrary fragment in the fragment zone hits the critical volume in the 3-dimensional angle. We assume that the fragments are projected with a uniform density in the fragment zone.

PSKADA = The probability that a certain function in the target is influenced if the critical volume is penetrated (the damage criteria).

Observe that the computations of effect in the different critical components of the critical volume differs only by the damage criteria, which is input (variable name "PSKADA").

For each critical component in the volume the total fragment effect, "PTOT", is computed as a summation of probabilities from all fragment zones by the following formula:

$$PTOT = 1-(1 - PUT_1) * (1-PUT_2) * (1-PUT_3) *...(1-PUT_L) \qquad (3)$$

where:

L is the number of representation lines against the critical volume and,

PUT_K = the part of the probability for kill due to fragment impacts represented by line K

The problems which have to be solved to compute the fragment effects in one volume are:

● Generation of representation lines for one fragment.

● Computations for each representation line of the probability that a fragment hits the volume in one solid angle.

● Computation of number of effective fragments in the solid angle which is represented by the representation line.

To generate representation lines and compute the probability for hits along the lines, there are two different techniques. In one technique components are described as cylinders, while the other uses polyhedrons to describe the components.

Basic assumptions for the calculations of fragmentation effects use the following assumptions:

(1) The effect of each fragment is independent of all other fragments.

The effect caused by fast fragments making holes through which the slower fragments could travel, is assumed to be negligible as the density of fragments as a rule is small.

(2) Fragment trajectories are straight.

Effects of fragments which after ricocheting hit a critical volume are ignored.

(3) Secondary fragment (spall) effects are ignored.

(4) The cross sectional area of the fragments in the trajectory is ignored.

In the computation of fragment retardation, consideration is taken of the cross sectional area when determining the penetration capability of the fragment.

To calculate fragment effects in volumes which are much longer than wide, e.g., wires, the critical volume description has to include the cross sectional area of effective fragments and the proportion of the radius of the wire which has to be hit to sever the wire.

(5) All fragments are projected uniformly in one fragment zone.

This uniform distribution of fragments is assumed around and along the longitudinal axis in one fragment zone. This causes limitations to, for example, yawing of the warhead.

(6) Real volumes should have a uniform retardation power for all fragment trajectories. Some grate or grill-like volumes have to be described differently for different trajectories of the fragments.

4.3.2 Determination of Number of Effective Fragments

An effective fragment has to have a penetration power greater than the shielding of the component. Thus an effective fragment has to have a penetration power, at the burst point, that is greater than the sum of the shielding, plus the reduction of the penetration power caused by fragment retardation along the representative line. The penetration power for a given velocity is determined by the mass of the fragment. The number of effective fragments in one fragment zone is all the fragments with a mass greater or equal to the smallest fragment that have enough power to penetrate the component.

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For fragments from uncontrolled fragmentation warheads, the smallest mass for an effective fragment is computed. With this mass, the number of effective fragments is derived by interpolation in the table describing number of fragments and masses. For controlled fragmentation the number of effective fragments is determined by checking what classes of fragments have the proper penetration power.

In both cases, one assumes that the basic velocity is the same for all fragments in the solid angle which is represented by the representation line.

4.3.2.1 Approximations When Determining Number of Effective Fragments N

In determining the number N of effective fragments, the calculation depends on the choice of representation lines, the uniformity of the shielding of the target against fragments and the distribution of the fragments into different mass classes.

Big changes in number of fragments for small changes in masses can give big errors. N is calculated from a distribution over number of fragments with a mass > M. The extreme case where controlled fragmentation gives k fragments with the same mass M and the mass of an effective fragment is calculated to be at least M-EPS (0 < EPS << 1.), the effect is going to be big. A small change to the calculation of the mass so that the mass is M + EPS will give nil effect where N = $\emptyset$. Errors such as this can be found by varying the coefficients for penetration and drag (see 4.3.3).

When calculating the smallest mass M, required for an effective fragment, fragment retardation is assumed to be uniform in the solid angle represented by the line. If the target is very inhomogeneous the number of representation lines need to be big to make it possible to calculate the retardation accurately. This is done by using more critical volumes and/or more fragment zones; the latter only if close burst points are expected. The effect of inhomogeniety of the target can be checked by studying the effect when the burst point is moved slightly around critical points. To check for anomalies, one makes repetitive runs with slight burst point location changes, to check for gross differences in the program output. If gross differences occur, the target description is checked for shielding by other real volumes, etc.

For certain types of real values, the retardation power must be changed for different warheads and sometimes even for the trajectory of the fragments (as with grill-or grate-like volumes).

The retardation power inside the volume has to be determined as a function of the angle of impact and presented area of the fragments.

In volumes describing big, empty rooms, such as holds of ships, the retardation power inside the volume must compensate for the drag (air) along expected fragment trajectories so that the penetration power of the fragment is correct after travelling through the volume.

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For volumes consisting of other materials than the unit material (See 3.1.1), the retardation power of the walls and the retardation inside the volume has to be proportioned to the penetration coefficient of respective material for a certain kind of fragments. The penetration coefficient for different materials changes in the same manner when the type of fragment is varied.

4.3.3 Fragment Retardation Along a Given Line

For a fragment with a certain mass and velocity, the penetration power is reduced as it moves through a number of real volumes and the air between them.

Fragment retardation is different in air and real volumes, thus the computations are made differently for the parts of the trajectory which are between the real volumes (air) and in the real volumes. Those parts of the trajectory are called air, respectively, and non-air distances.

The penetration power, in non-air distances, is reduced linearly, penetration power is thus a linear function of the distances which the fragment travels through the walls and inner space of the real volume.

The total retardation in non-air distances is the sum of distance times the retardation power for each wall or inner space. (See 3.1.1 and Figure 2 on fragment retardation in a real volume.)

In a complex target with many real volumes with some surrounded by others, the computations are made in a similar way. In Figure 12, the rule is depicted that in each point in the trajectory the closest surrounding real volume defines the geometry and retardation power.
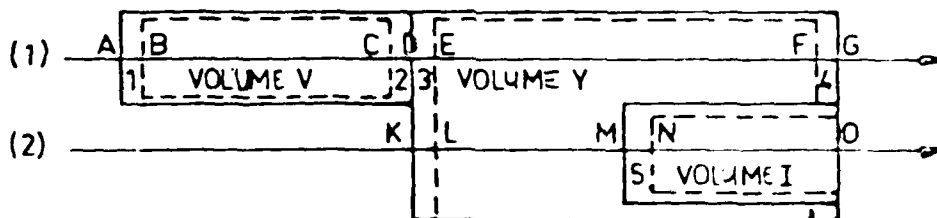

Figure 12. Fragment Retardation in a Non-Air Distance

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Walls 1 and 2 are parts of volume V; walls 3 and 4 of Y; and, wall 5 of I, which does not have a wall numbered 6, as this wall is a part of volume Y. S_i = retardation power in wall i, i = 1,5 and volume i's innerspace i = I, Y, V. The total retardation VAG along AG for trajectory 1 is:

$$VAG = ABxS_1 + BCxS_V + CDxS_2 + DExS_3 + EFxS_Y + FGxS_4. \tag{4}$$

Total retardation along KO for grajectory 2 is:

$$VAG = KLxS_3 + LMxS_Y + MNxS_5 + NOxS_I. \tag{5}$$

In the air the retardation power of the fragments is reduced expo-netially as a function of distance travelled. The following variables are used using SI-units (See Figure 13.)

I = number of non-air distances

M = mass of fragment

V = basic velocity of fragment

CGENOM = the penetration coefficient of the fragment in the material used in describing the target.

L = the drag coefficient of the fragment type

W_ϕ = Ith air distance after the first real volume

VAG_k = the total retardation in the kth non air distance

The retardation power in air is reduced exponentially because the velocity after W meter in air is:

$$V_1 = V * e^{-\frac{L*W}{M^{1/3}}} \tag{6}$$

The penetration power for a certain mass and velocity is:

$$G = CGENOM * M^{1/3} * V_1 \tag{7}$$

Combining those two formulae, we get for W_ϕ in meters of travel in air:

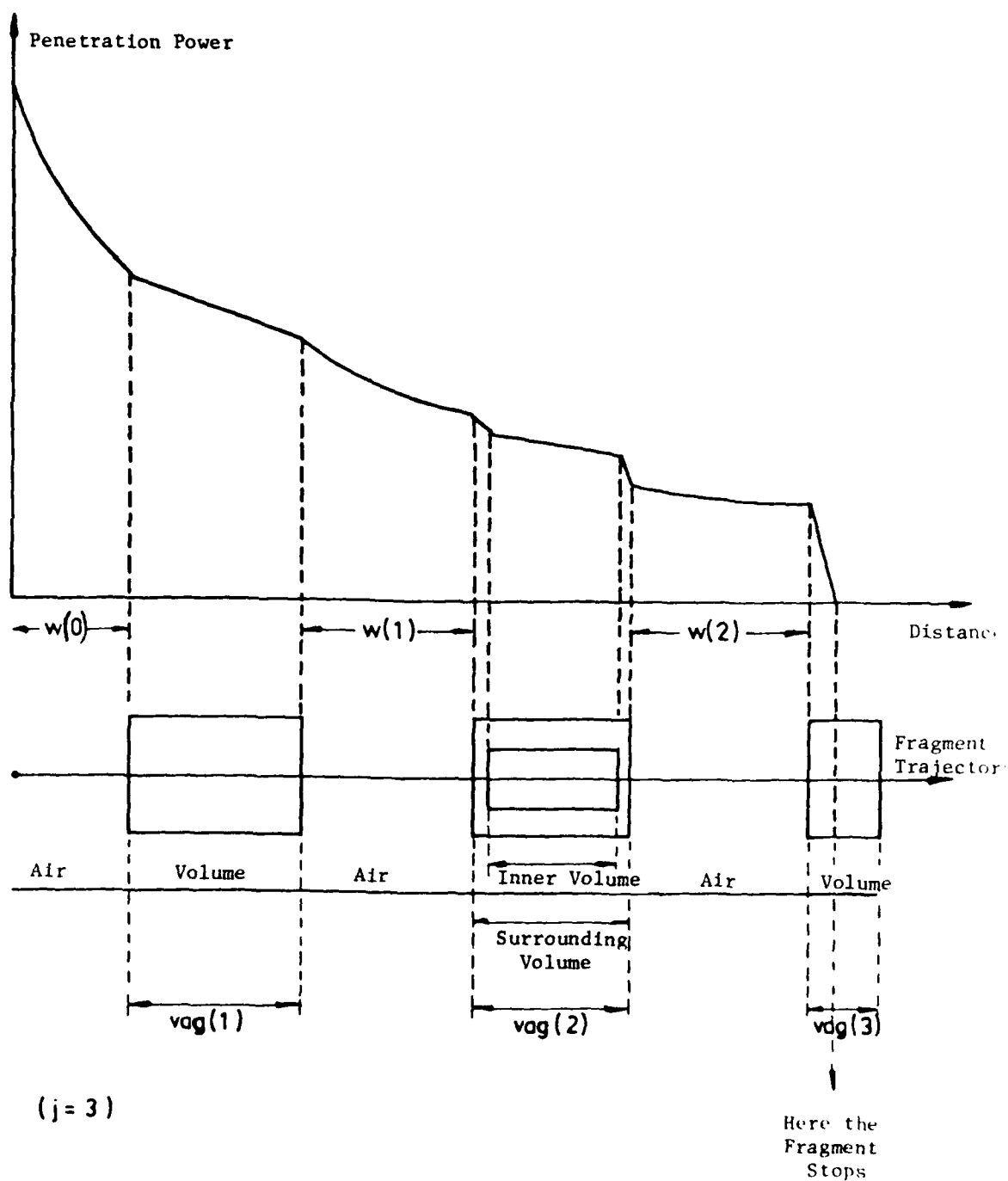$$G = CGENOM * M^{1/3} * V * e^{-\frac{L*W_\phi}{M^{1/3}}} \tag{8}$$

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Figure 13. The Change of the Penetration Power
Along a Given Trajectory

If the trajectory intersects a group of real volumes, after the air distance W_ϕ, with a total retardation of VAG_1 and then goes through air again (W_1 meter) the penetration power is:

$$G = \left(CGENOM * M^{1/3} * V * e^{-\frac{L*W_\phi}{M^{1/3}} - VAG_1} \right) * e^{-\frac{L*W_1}{M^{1/3}}} \qquad (9)$$

Thus we obtain the following general formula for an arbitrary number of air non-air distances. For a certain mass and basic velocity, the penetration power of the fragment (G) at a certain point in the trajectory is calculated by the following algorithm.

$$G = F(J,X) \qquad (10)$$

$$X = M^{1/3} \qquad (11)$$

$$F(1,X) = V \times CGENOM \times \frac{e^{-X \times L \times W_o}}{X} \qquad (12)$$

$$F(K+1,X) = (F(K,X)-VAG_K) \times e^{-X \times L \times W_K} \qquad (13)$$

$$K = 1, \ J - 1$$

The algorithm assumes that the velocity of the fragments is not less than the sound velocity in any air distance. This is a limitation only for big fragments and when the critical volume is situated without any protection in air when the effect should be somewhat greater. In all practical cases $J < 3$.

The fragments produced with controlled fragmentation are checked for each class of masses if the penetration power exceeds the shielding of the critical volume, which means that the fragments are effective. For the case with non-controlled fragmentation, the mass (M) is computed; and is equal to G (the shielding of the component times X ($X = M^{-1/3}$ is substituted for $M = X^{-3}$).

All fragments with a mass > M are assumed to be effective.

4.3.4 Representation Lines and Fragment Impact Surfaces in a Critical Cylinder

The method is a development of an analytical fragment effects calculation where the components are described as line segments (Nomark-68 method B), such as in LMP-3.[7] By substituting the line segment with critical cylinders, the area of the impacted surface can be calculated as a function of the direction of the trajectory and thus provide a more accurate determination of retardation.

4.3.4.1 Brief Description of the Algorithms

From a certain burst point an interesting interval BE of the axis
of the cylinder is computed so that the whole cylinder is between the two
cones which intersect the axis of the cylinder in points B and E. The
cones have their apices in the burst point and the axes common with the
warhead. For all cones(which are the limits of the fragment zones) the
intersections with the line BE are calculated (C,D), see Figure 14.

For each part of the line (BC, CD, DE) a line is generated from the
burst point to the mid point (R1, R2, R3). These are the representation
lines for fragments in the fragment zones intersecting the cylinder axis.
The mean fragment trajectory is calculated along the representation line
until it intersects the surface of the cylinder. In those cases where B
or E is a point in the infinitive and the representation line does not in-
tersect the cylinder, the mean fragment trajectory is calculated, using a
more accurate method, to have the line intersect the cylinder within the
fragment zone. To calculate the probability for hit for the representation
line, the representive area of the cylinder, as seen from the burst point,
is calculated. This is calculated as a parallel projection of the cylinder
on a plane having the representation line as perpendicular and with the mid
point R_i, i = 1,2,3. By normalizing the area the solid angle, which is seen
from the burst point, is calculated. The probability for hit for one frag-
ment, in the area represented by the representation line is the ratio between
the solid angle calculated above and the solid angle for the whole fragment
zone.

4.3.4.2 The Projected Area of the Cylinder in One Fragment Zone

Note the portion of the cylinder which is inside one fragment zone.
From the warhead, a line is drawn to the center of the intersection of the
axis of the cylinder. Through the point of intersection, a surface is gen-
erated perpendicular to the representation line. Onto this surface, the edges
of the cylinder are projected, as is the axis of the cylinder, and the limits
of the fragment zone, Figure 15. The intersections of the limits of the frag-
ment zone and the cylinder are approximated by straight lines. The elliptical
projections of the ends of the cylinder are approximized by triangles so that
the area of the approximate figure approaches the area of the real figure. The
area of the approximate figure (YTA) is a sum of a number of convex polygons.

The solid angle (Y) for the cylinder inside the fragment zone is cal-
culated by:
$$Y = YTA/A^2$$
(14)
where A is the distance between the warhead and the projection
surface.
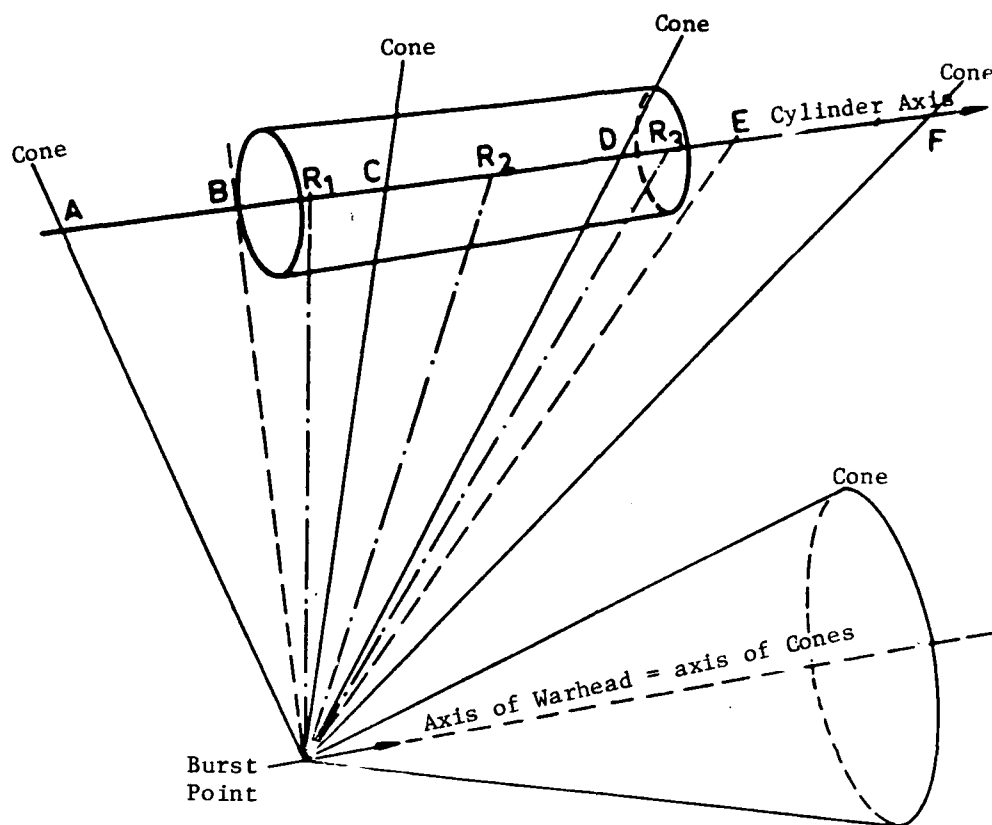
The intersections of the cones and the axis of the cylinder:

A,C,D,F

Intersecting interval on the axis of the cylinder: BE

Note the three intersecting parts of the cylinder:

BC, CD, DE

The representation lines are drawn to the mid-points: R_i

Through which the plane perpendicular to the line is placed.

Figure 14. Lines Against a Critical Volume

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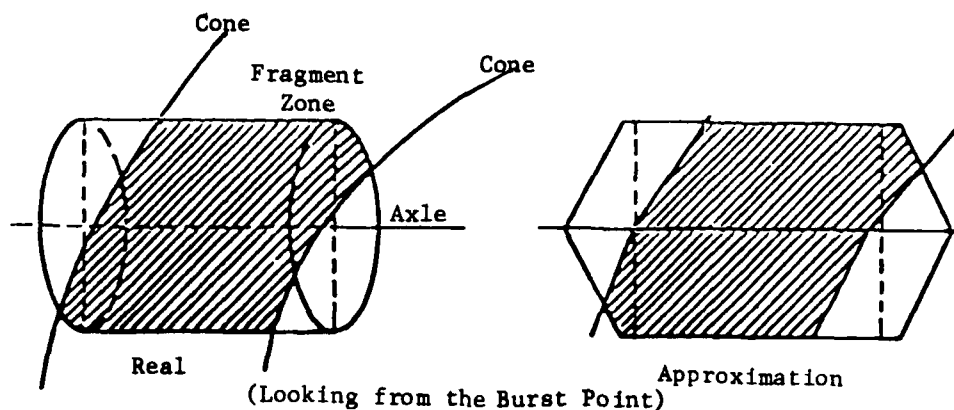
Figure 15. The Area of the Cylinder in one Fragment Zone

4.3.4.3 Views on the Approximations

Calculation of the area uses a number of approximations which are not very well suited for prediction of close range effects. These are:

(1) The surface is projected parallel onto a plane instead of being projected on a sphere.

(2) If a cone (limit of a fragment zone) does not intersect the axis of the cylinder, it is considered not to intersect the cylinder.

The second point is illustrated on Figure 16. In this case the whole cylinder is assumed to be in the fragment zone limited by cone 2 and 3.

Figure 16. Fragment Zone Intersections on the Critical Volume

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In the phase of the calculations concerning close range and direct hit effects, some critical elements are killed depending on the vulnerability, the power of the high-explosive and the protection (real volumes). This has the effect that the errors 1 and 2 do not have any influence for big warheads.

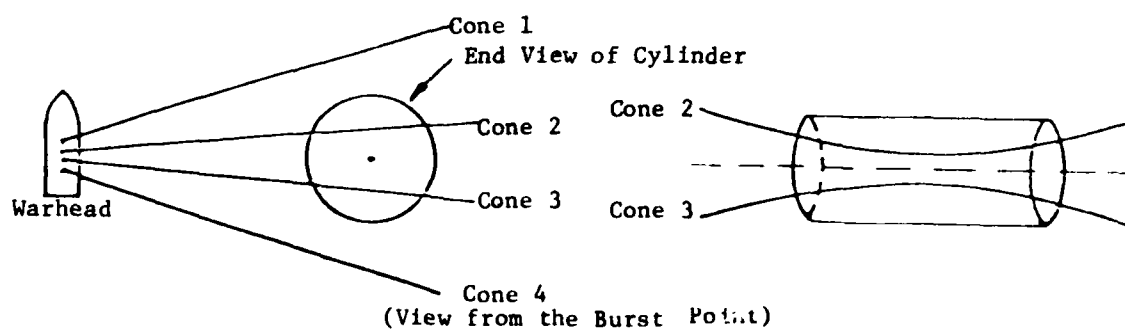For each fragment zone and the corresponding part of the cylinder which lies in the zone, only one representation line is generated. This means that a greater number of cylinders has to be used when the retardation power of the target is not homogenous.

An analytical model with fixed representation lines, as described above always gives the same result for a certain burst. A good way to check the result is to move the burst point and change attitude slightly, this gives a different retardation of the fragments and a different representive area of the fragments.

To describe a critical volume with a cylinder is a very good approximation for cables and other volumes with a small width to length ratio. To describe a box with considerable retardation in its walls, the cylinder has to be surrounded by, or surround, a corresponding real volume. Depending on the description, the shielding of the critical volume is chosen so that it compensates for the difference in retardation, and the damage criteria is chosen so that it compensates for the difference in vulnerable area.

4.3.5 Representative Areas of Fragments and Representation Lines Against Critical Surfaces

This method is under development and is not yet incorporated in VERKSAM. It uses a simulation model (Hagwall-67 [5]), where the critical volumes are described as parallelepipedes, a model which gave relatively long computation times.

To the different sides in an arbitrary convex polyhedron (e.g., a real volume) each side can have a number of areas. To each area a representation line is generated where the side can be seen from the burst point. Each area is given a shielding factor which describes the vulnerability, a damage criteria that gives the probability that a function is effected if hit by an effective fragment, and a vulnerable area which is reduced when the angle of impact is small. The probability for a hit of one fragment in one fragment zone is computed as the ratio between the solid angle of the vulnerable area as seen from the burst point and the solid angle of the fragment zone. The whole vulnerable area is assumed to be in one fragment zone; see Figure 17.
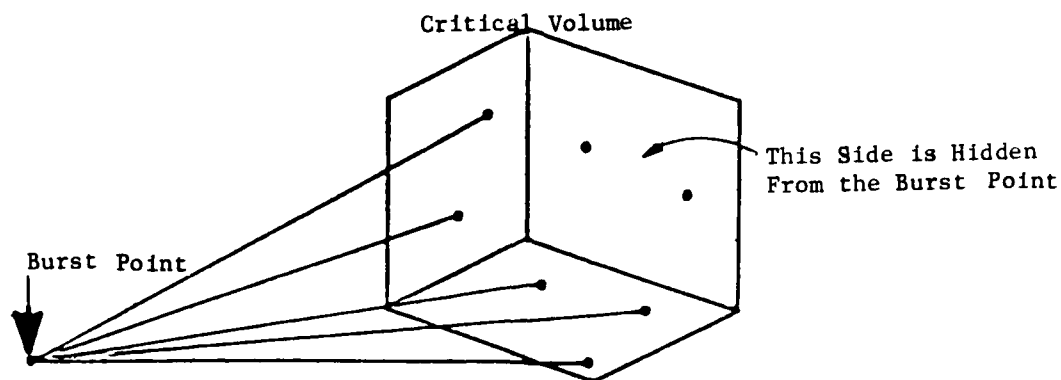
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Figure 17. Lines Against Critical Surfaces

4.3.6 Approximations When Determining the Probability that a Fragment Hits a Vulnerable Surface

The accuracy of the calculation of P depends on:

(1) The description of the shape and the vulnerable surface of the critical volume.

(2) Approximations used for the calculation of the projected area of the vulnerable surface for a certain representation line. The error depends on the distance between burst point and critical volume.

(3) The description of the warhead, especially the size of the fragment zones.

Point 1) describes the worst of the problems, as it includes the estimate of the vulnerability and the transformation of it to a number which is a measurement of the vulnerability). Note that the shape of the critical volume gives a vulnerable area that is dependent on the direction while the damage criteria does not depend on the direction.

Point 2) means that an error in the second or third significant digit, at the calculation of the area, decreases with the distance raised to the second power. That is the distance between the burst point and the critical volume (see 4.3.4.3).

Point 3) is illustrated in Appendix A and shows that variations in the choice of the sizes of the fragment zones gives negligible effect in PUT (the probability of kill).

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When the burst points are expected to be close to the target, the size of the fragment zones ought to be so small that one critical volume intersects several of the fragment zones. Otherwise, the accuracy of the calculation of the areas will suffer (see point 2).

4.3.7 Important Approximations for the Calculations of Fragment Effects

Fragment effects in each individual critical volume are calculated according to Section 4.3.1 for each critical component as a summation of the probabilities of kill (PUT), calculated for different representation lines.

$$PUT = 1-(1-P)^N \tag{15}$$

where:

N = number of effective fragments in the fragment zone with the specified representation line.

P = the probability that if an effective fragment hits such a surface in the critical volume, a certain function is influenced.

(P = PTRAFF*PSKADA, see Section 4.3.1)

The calculations of N and P use a number of approximations in the input and in the algorithms, which together give some errors in the result. The influence of the errors on PUT is shown by the following example:

Note that with the Equation 15 N or P is multiplied by 2, PUT has a maximum of 0.3, when in the interval (0.1, 0.9). When PUT is in any other interval, the change is considerably less. See Appendix A for PUT's sensitivity to changes in N and P.

4.4 SYNTHESIS OF EFFECTS IN DIFFERENT FUNCTIONAL SYSTEMS

Using the computed probabilities for kill in the different parts of the target, the probabilities that the technical and tactical systems of the target are in certain states can be computed.

The calculations can be made for each attack but also as a mean for a great number of attacks.

A functional system is made of chains of sequentially and/or redundantly effective components, where the effect in one component is independent of effects on the remaining components. In a simple, sequential system all components must function if the system shall operate. Redundant components are those of which at least one of the parallel components must function to have the system operate. Redundant components are used for especially vulnerable components in a functional system, e.g., two separate electrical wires or hydraulic lines to perform the same task, etc.

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To make the program more versatile, two models are used. The first model assumes a simple sequential construction of the functional systems, but can take into consideration repair times. One example to use this model on is: aircraft parked on a base. The second model is used to calculate effects in technical and tactical systems which are constructed of complex chains of redundant and sequentially effected components, whose systems are 'nterdependent. An example is a ship.

4.4.1 Effects Measured by Repair Times in Sequentially Constructed Functional Systems

The model calculates the probabilities that a repairable system is inoperative longer than certain specific periods of time. For a target with many systems requiring repair which targets are alike, the program also computes the probability that at least k systems are down longer than certain specified periods.

In the example with the airbase each aircraft is a repairable system with the two conditions: ready for a mission or not ready for a mission at any certain time.

The time periods which influence the down-time of the system are described by the following sequence of events after an attack:

The system is checked for damage (diagnostic time). If any component is non-functioning, it is transported to a suitable repair facility (transport time). The system is divided into a number of subsystems, which are repaired or exchanged and checked concurrently.

In each subsystem, the components are repaired sequentially, that is, their repair times are additive. One exception is components in the same exchange group. Those components are repaired or exchanged concurrently with a common repair time. After the repair, a common check and functional test is made on components in the same group. When all unit-replaceable subsystems are operating properly, they are transported back to the airplane.

4.4.1.1 Calculation of the Probability that the Repair Time is > T Hours

The repair time is divided into even intervals with the length TS$\overline{}$ $_u$. The continuous time, TID, corresponds to the index ITID, which is the quota. TID/TSTEG rounded to the closest integer. ITID thus corresponds to the time interval ITID*TSTEG + 0.5 * TSTEG. Let MXT be the index corresponding to last time interval. ITID will then have all values from 0 to MXT. P(H) is the probability that the event H occurs. In this case we will separate events of two types, the first being the event that time = k time units when k < MXT and the second that the time is $\geq$ MXT. The latter is thus the sum of events of the first type where k is summed from MXT to ∞.

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In the calculations we will separate steps made parallel and serially in time.

(1) Calculations made for each subsystem:

$S_k(i)$ = P (repair + test time for subsystem k is i time units).

(2) If the system consists of M subsystems that can be repaired concurrently, the following is calculated: $S(i)$ = P (repair + test time is i time units that is:

$S(i)$ = P (at least one subsystem has a repair and test time that is i time units)

which gives:

$$S(i) = 1 - (1 - S^{(1)}(i)) * (1 - S^{(2)}(i)) * \ldots (1 - S^{(m)}(i)) \qquad (16)$$

(3) As a result, the following is calculated:

$S(\emptyset)$ = P (the system is working)

and

P (the system is inoperable for more than i time units) =

$$\sum_{j = i + k}^{\infty} S(j) \qquad \text{for } i > \emptyset$$

where k is the time for transport to and from the repair facility plus time additions of the same kind.

$S_m(i)$ in point one is calculated with the following three recursive equations.

In detail, these steps are:

(a) look at the components of just one test group. Suppose that $P_k(L)$ = P (component k with the repair time L is killed) where L = (repair time for the component)/TSTEG (rounded).

In these cases where more than one component is in an exchange group, their probabilities of kill are set to $\emptyset$. For all but the first in the group which gets the probability that at least one component in the exchange group is killed (see Equation 16). Thus, we can assume that for all components with a positive probability of kill, their repair times can be added in any order.

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We want $R_n(i) = P$ (the repair time for the n first components in the test group is i time unit).

Assuming that $L > \emptyset$.

$$R_o(i) = \begin{cases} 1 \text{ for } i = 0 \\ 0 \text{ for } i > 0 \end{cases} \qquad (17)$$

$$R_n(i) = 0 \text{ for } i < 0 \text{ and all } n \qquad (18)$$

$$R_{n+1}(i) = R_n(i) \times (1 - P_{n+1}(L)) + R_n(i-L) \times P_{n+1}(L) \text{ for } i < MXT \qquad (19)$$

$$R_{r+1}(MXT) = R_n(MXT) + P_{n+1}(L) \times \sum^{\min(L,MXT)} R_n(MXT-j) \qquad (20)$$

If the repair time for one component is < TSTEG/2, it is ignored in the computations.

(b) Check the test group k with n components. To the repair times, calculated in (a), the test time ITID is added for the whole group where ITID is the test time for group k. Calculate $T_k(i) = P$ (repair + test time for test group k is i time units for k < MXT) and $T_k(MXT) = P$ (the repair test time for test group k is $\geq$ MXT time units).

For ITID < MXT:

$$T_k(i) \begin{cases} = R_n(0) & i = 0 \\ = 0 & 0 < i \leq ITID \\ = R_n(i - ITID) & ITID < i < MXT \\ = \sum_{j=MXT-ITID}^{MXT} R_n(j) & i = MXT \end{cases} \qquad (21)$$

For ITID $\geq$ MXT:

$$T_r(i) \begin{cases} = R(0) & i = 0 \\ = 0 & 0 < i < MXT \\ = 1 - R(0) & i = MXT \end{cases} \qquad (22)$$

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(c) Check subsystem m, which consists of NTEST test groups. The total repair and test time for all test groups is calculated as:

$$S_m (i) = S_{NTEST}(i)$$ (23)

where

$S_k (i) = P$ (the total repair and test time for the k first test groups in subsystem m is i time units, when i<MXT)

and

$S_k (MXT) = P$ (the total repair and test time for the k first test groups in subsystem m is $\geq$ MXT time units)

$S_m(i)$ is calculated from the result of (b), $T_k(i)$ by:

$$S_0(i) = \begin{cases} 1 & i = 0 \\ 0 & i > 0 \end{cases}$$ (24)

$$S_{k+1}(i) = \sum_{j=0}^{i} S_k(i-j) \times T_{k+1}(j) \qquad 0 \leq i < MXT$$ (25)

$$S_{k+1}(MXT) = S_k(MXT) + T_{k+1}(MXT) - S_k(MXT) \times T_{k+1}(MXT) + \\ + \sum_{j=0}^{MXT-1} T_{k+1}(j) \sum_{l=1}^{j} S_k(MXT-1)$$ (26)

4.4.2 Synthesis of Effects in Functional Systems with Dependent Redundant Components

For complex functional systems constructed by chains of redundant and sequentially effective components, one may conveniently calculate the effect in the independent systems analytically and then simulate the effect for the depending systems. A functional system is constructed hierarchally with several levels. Using the lowest level, subsystems are defined that are independent. From the subsystem, higher levels of systems are constructed to end with technical systems in the next to highest level and tactical systems in the highest level.

The calculations are made by Monte-Carlo simulation. Depending on the probability of kill for one subsystem, an event is randomized, gaging whether the subsystem is killed or not. By doing this for all subsystems, one may easily calculate whether the higher level systems are killed or not. By repeating the randomizing process the probability that a tactical system is killed can be calculated as the ratio of (number of times the system was killed)/(number of simulations). To reduce the variance, antithetical variables are used (Anderson-74)[6].

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4.5 COMPUTATIONS OF INTERSECTIONS BETWEEN A STRAIGHT LINE AND A HIERARCHALLY CONSTRUCTED TARGET DESCRIPTION

Some rules for a hierarchally constructed target description are:

(1) a simple and logical way to do it for the person who describes the target

(2) simple rules which provide an added safety so the description can be checked by the program

(3) possibilities to optimize the computations

Point (3) is used mainly at burst point generation and at the calculations of fragment retardation. With a hierarchical structure, volumes not affected by the calculation of intersections, can easily by ignored. This is done by first considering the intersections with volumes in the highest level of the hierarchy and then only look at volumes which had an intersection with the trajectory. This is repeated down to the lowest level in the hierarchy.

To optimize farther the calculations, the interval interest on the trajectory is given as well as a maximum number of intersections. Starting at the end of the interval, intersections with the imaginary volumes are calculated. As each imaginary volume corresponds to a target type with its own coordinate system, the line (trajectory) has to be transformed to this system. Now volumes of the next order are examined and so on until the end of the interval or the maximum number of intersections is reached; see Figure 18.
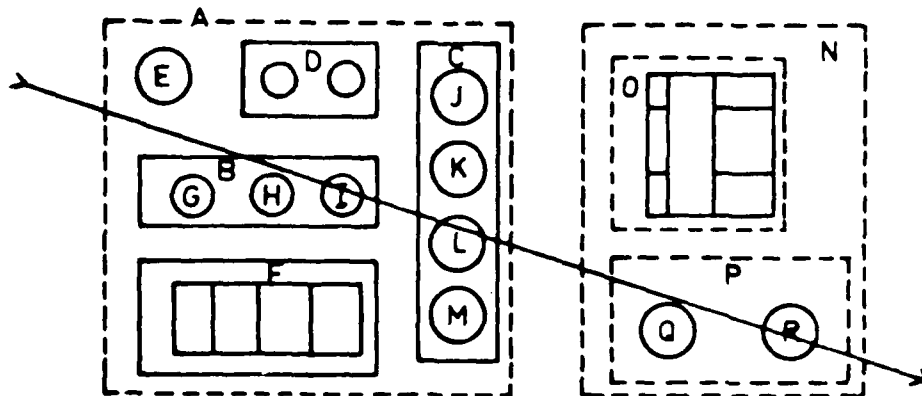
Calculations of intersections are made in the following order:

A, N, B, C, D, E, F, G, H, I, J, K, L, M, O, P, Q, R.

These intersections are saved: B, I, C, L, R as imaginary volumes are only a help for the calculations.

Figure 18. Intersections Between a Straight Line and a Target

5.   FIRE AND LEAKAGE

The effects from and the probability for fire and leakage cannot be calculated in this model. There is no basis to calculate effects of fire. To get an idea of the probability that a fire occurs as a consequence of hits of fragments, functional systems consisting of critical volumes with possibilities for fire can be used.

Primary and secondary flooding are consequences of holes in the outside and inner hulls and/or bulkheads of a ship. To calculate leakage from fragment effects the following method can be used, which has been tried in an earlier model. For a critical component where leakage can occur, the smallest mass of a fragment that penetrates the shielding is computed. The fragments are divided into classes of masses with a given number of fragments in each class. For each class with masses greater than the mass necessary to perforate, the areas of the expected holes are computed under the assumption that the fragments create holes independently. The area is:

$$HAREA = \sum_{i=1}^{L} N_i * AREA_i \qquad (27)$$

where:

L = number of classes of fragments with effective fragment mass

and:

$$AREA_i = \frac{MASS}{Density}^{2/3} \cdot C \qquad (28)$$

N_i = number of expected fragments in class i against the critical volume, which is:

$$N_i = YTF*ANTAL_i \qquad (29)$$

where:

YTF = probability that one fragment in the fragment zone hits the critical volume and,

$ANTAL_i$ = number of fragments in class i

C = constant depending on the presented area, type of hole and whether the fragment makes a hole in the opposite wall when leaving.

The results from the fragment effects phase give for this solution the expected area of the holes in the critical volume where leakage can occur. By adding the areas of the hole without taking into consideration that two fragments can use the same hole, the total area calculated will be greater than would occur.

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6.   EXAMPLE OF THE USE OF VERKSAM AGAINST A SEA TARGET

6.1   ABSTRACT

The target in this example has been used to compare warheads. It is not a real ship but has as its main components an engine room and cabin. The target is simple compared to the real ships described for VERKSAM, but will then be easier to understand. The basis for this section is a report describing a method to compare warheads in a simplified way, using the stand-are target, A. Fischer.[2]

6.2   MAIN COMPONENTS OF THE STANDARD TARGET

An analysis of vulnerability calculations made by VERKSAM on real ships shows that the following five types of spaces can be found.

(1)   <u>Cabins</u> – Spaces of type, etc. The size is limited and bulkheads are thin; the content of the cabin consists of many sensitive critical components.

(2)   <u>Engine Room</u> – Spaces of type–engine room, as a rule, are bigger than cabins, bulkheads often consist of the planking and are thus thick. The room has a content of several big critical volumes with great shielding.

(3)   <u>Cells</u> – Spaces without critical volumes; the thickness of the walls are varying. Typical spaces are chain locker, water tank, etc.

(4)   <u>Hold</u> – Big rooms with thick bulkheads and deck. The load can vary, but is as a rule not critical for the functions of the ship but often for the mission.

(5)   <u>Special Spaces</u> – E.g., ammunition room, gun--these spaces can be treated as critical volumes where a direct hit, after penetration of the armor, will kill the function. Fragments will not have any great effect.

Against the most common effects of warheads, fragments and blast, the different spaces described above are vulnerable as follows:

<u>Cabins</u> – are sensitive to fragments and to blast if the explosive volume is relatively large compared to the volume of the cabin.

<u>Engine Room</u> – has the same characteristics as the cabin but is less vulnerable.

<u>Cell</u> – is mainly sensitive to blast, but the explosive volume has be large enough compared to the volume of the cell.

<u>Hold</u> – is relatively insensitive, but the cargo is sensitive to fragments.

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Different types of ships consist of the spaces described in different proportions. An attack ship for example, consists mostly of cabins and engine rooms, while a landing ship consists of cells, holds, engine room and a few cabins. Those different characteristics of the ships make it difficult to compare effects for one type of ship to those for another.

6.3   PRINCIPLES FOR EVALUATION

Knowledge in the vulnerability calculations area shows that the fragment effects can be calculated accurately. When we come to blast effects, there is a small basis for estimating how much explosive is needed to destroy the contents of a certain volume. Thus, the effect of a warhead can be calculated as follows:

(1)   The critical volume of a cell is determined. By detonations in caves* the blast can be determined and provide measurement of the volume of the cell which can be destroyed.

(2)   Effects in a cabin are calculated. As a target, a standardized cabin description is used. First a check is made of the blast needed to destroy the cabin; and, if total destruction is not predicted, the mean number of critical volumes killed by fragment effects is determined for a Monte Carlo sample of different burst points in the cabin.

(3)   Effects in an engine room are calculated as for cabins.

(4)   Effects in a hold are calculated or judged. This part of the evaluation can be made as for 2 and 3 above. The cargo is variable and is therefore   not standardized.

6.3.1   Standard Target Cabin

This standard target represents spaces in a ship which have many components, electrical, etc. See Figures 19 and 20. Those cabins have about the same volume independent of type of ship, while the number of cabins varies with the type of ship. The components are, as a rule, sensitive and critical for functions of the ship. The crew is an essential part of those critical components. The cabin has been made to correspond to the vulnerability of the spaces mentioned above. Dimensions are 3.6 x 2.1 meters. The bulkheads are 3.5 millimeters of aluminum. The critical volumes are represented by six different types of cylinders as indicated in Table 1.

Typical component data are given in Table 2.

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*   A series of detonation tests were performed in caves in Sweden from which empirical data were obtained. These data formed the basis for the calculations of volume destruction due to blast.

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Figure 19. Cabin from Above

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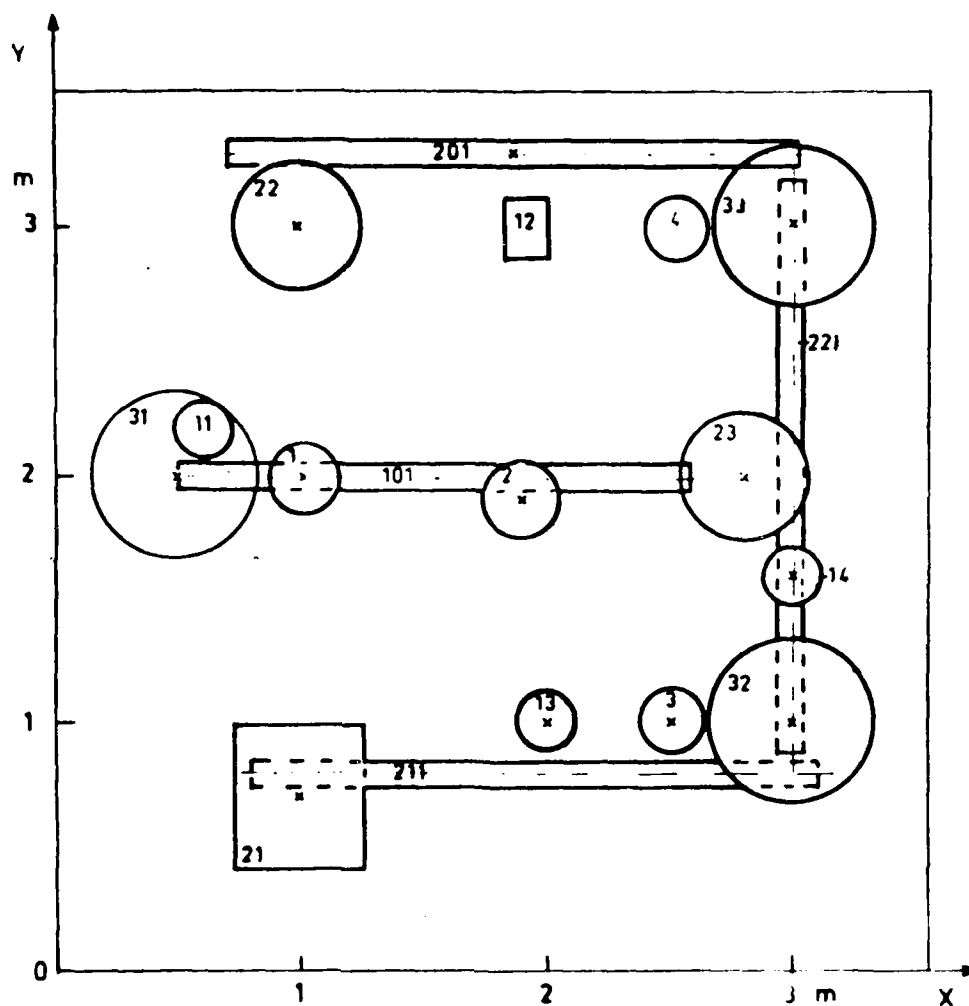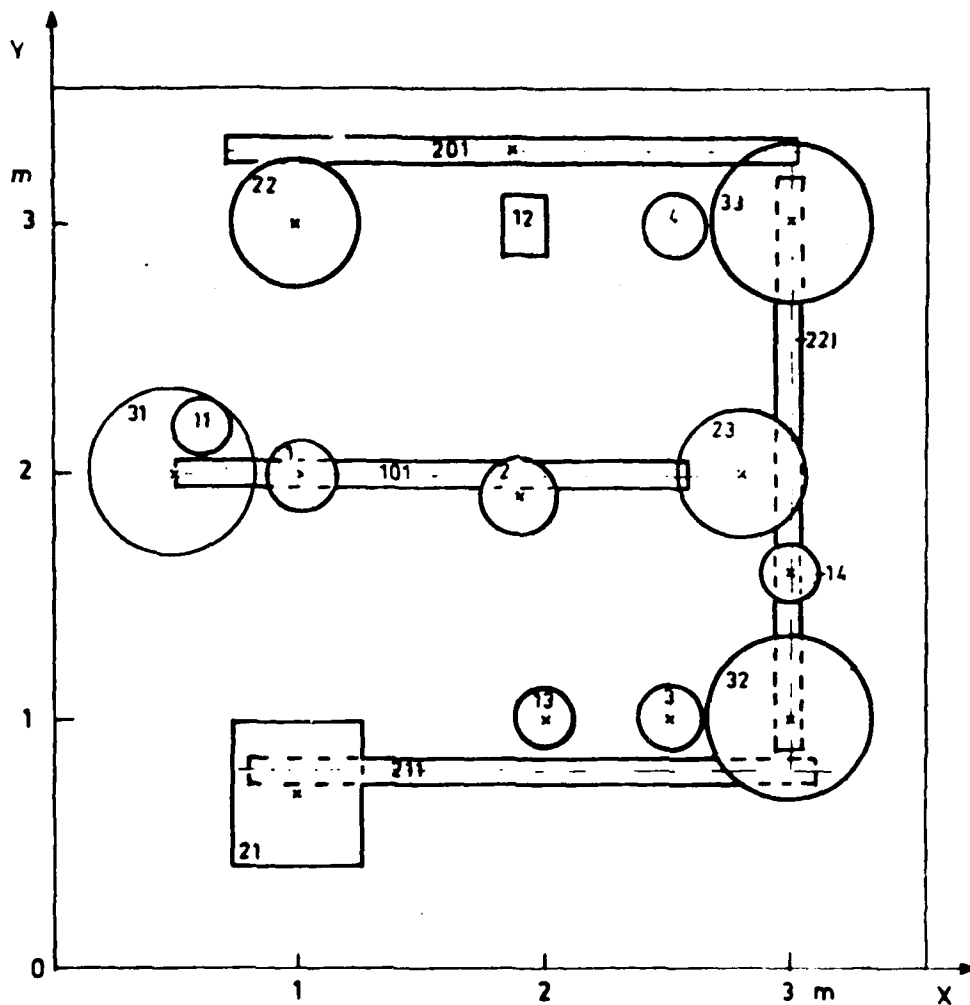
Figure 19.   Cabin from Above
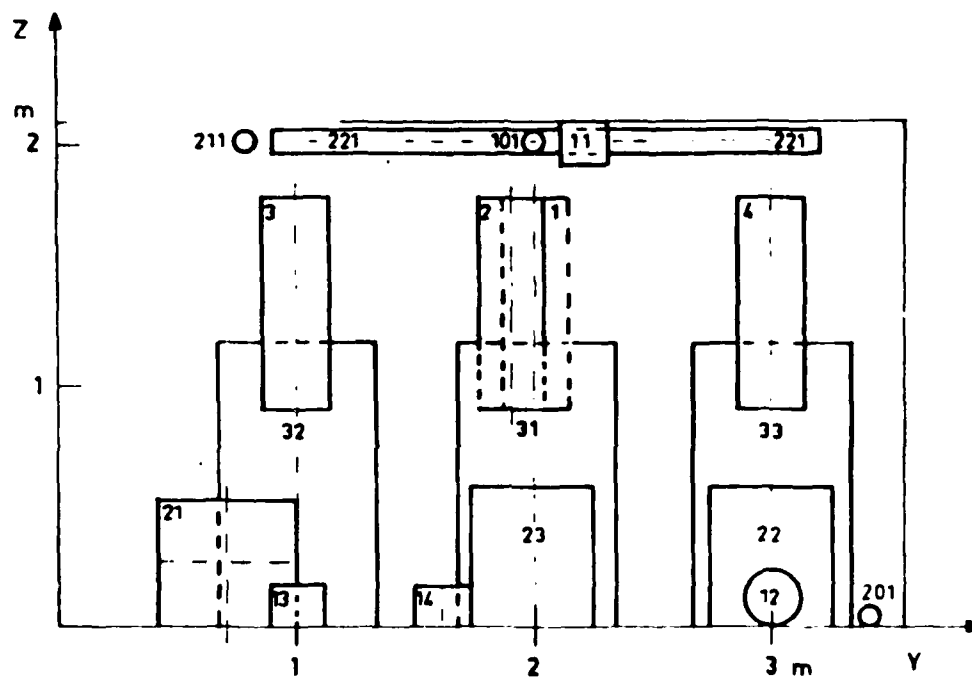
Figure 20. Cabin from the Rear

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Table 1.   Cabin Component Details

Type	Length of axis cm	Radius cm	Shield-ing mm Al	Damage - Criteria %	Number of	Can Represent
1	18	12	3	72	4	Small indica-ting devices
2	59	26	3	67	3	PPI, etc.
3	119	33	3	80	3	Radar
4	90	14	2	90	4	Personnel (sitting)
Cable 1	208	5	10	43,16,6,1	1	Cables*
Cable 2	230	5	10	11,5,1,1	3	Cables*

Table 2. Cabin Critical Component Details

Number	Shielding in mm Dural	Coordinates for the Ends of the Axle of the Cylinder (cm)						Radius (cm)	Damage Criteria %				
		X_1	Y_1	Z_1	X_2	Y_2	Z_2						
1	2	100	200	90	100	200	180	14	90				Missile Officer
2	2	190	190	90	190	190	180	14	90				Chief
3	2	250	100	90	250	100	180	14	90				Weapons Off
4	2	250	300	90	250	300	180	14	90				Artillery Off
11	3	60	220	192	60	220	210	12	72				Controls
12	3	182	300	12	200	300	12	12	72				Switch
13	3	200	100	0	200	100	18	12	72				Accelerometer
14	3	300	160	0	300	160	18	12	72				Rategyro
21	3	100	41	26	100	100	26	26	67				Video
22	3	100	300	0	100	300	59	26	67				Switch
23	3	280	200	0	280	200	59	26	67				Controls
31	3	50	200	0	50	200	119	33	80				Indicator
32	3	300	100	0	300	100	119	33	80				Relay
33	3	300	300	0	300	300	119	33	80				Head Indicator
101	10	50	200	205	258	200	205	5	43	16	6		Sensitive Cable
102	10	50	200	205	258	200	205	4	43	16	6		" "
103	10	50	200	205	258	200	205	3	43	16	6		" "
104	10	50	200	205	258	200	205	2	43	16	6		" "
201	10	70	340	5	300	340	5	5	11	5	1	1	Cable
202	10	70	340	5	300	340	5	4	11	5	1	1	Cable
203	10	70	340	5	300	340	5	3	11	5	1	1	Cable
204	10	70	340	5	300	340	5	2	11	5	1	1	Cable
211	10	80	80	205	310	80	205	5	11	5	1	1	Cable
212	10	80	80	205	310	80	205	4	11	5	1	1	Cable
213	10	80	80	205	310	80	205	3	11	5	1	1	Cable
214	10	80	80	205	310	80	205	2	11	5	1	1	Cable
221	10	400	90	205	400	320	205	5	11	5	1	1	Cable
222	10	400	90	205	400	320	205	4	11	5	1	1	Cable
223	10	400	90	205	400	320	205	3	11	5	1	1	Cable
224	10	400	90	205	400	320	205	2	11	5	1	1	Cable

6.3.2 Standard Target Engine Room

The term engine room, means all spaces, opposed to cabins, with heavier type of equipment, i.e., engines. Those spaces vary in size and equipment much more than do cabins. Examples are: turbine room, diesel engine room, transformer room and steering machine room. Thus, it is a bigger problem to make a standard target out of the engine room that of the cabins. Note the engine room layout shown in Figures 21 and 22.

The space chosen is the result of much work, checking all spaces that could fit. There is no standard engine room; the engine room shown in these figures is that of a corvette. The component data for this engine room is given in Table 3.

The dimensions are: 7.4 x 7.9 x 4.1 meters with bulkheads five and six millimeter iron. The critical volumes are of six different types, see Table 4.
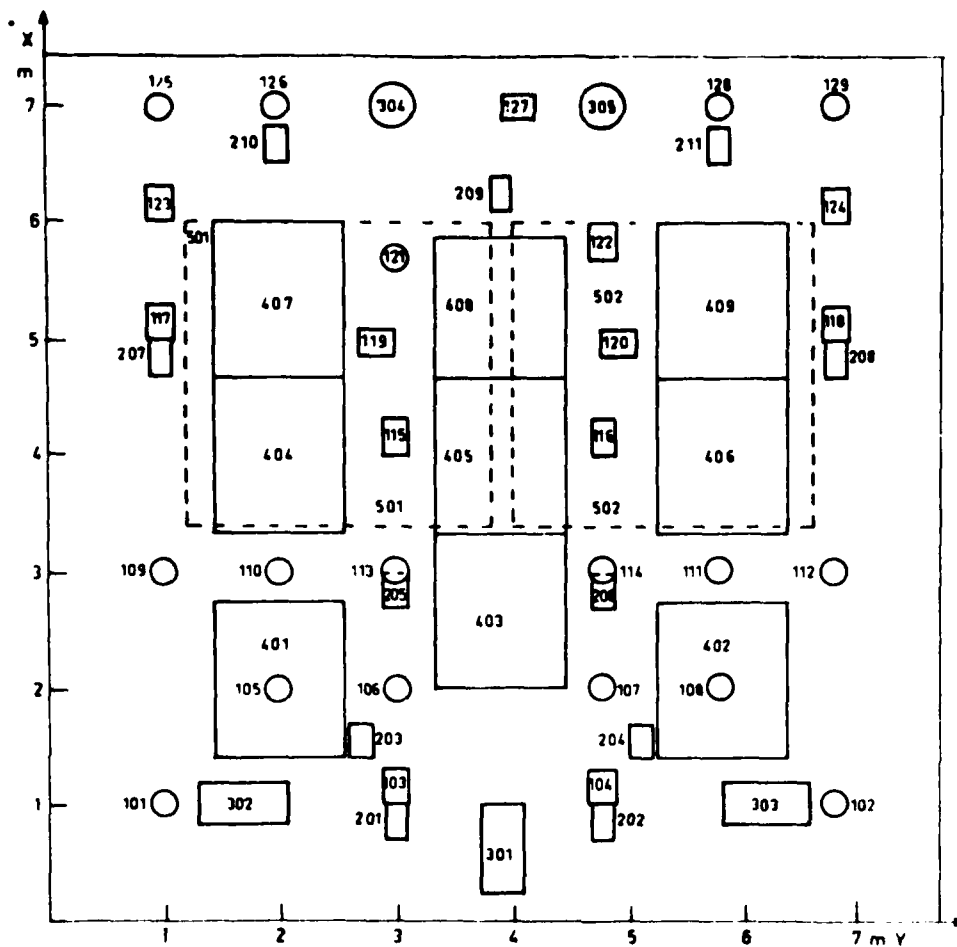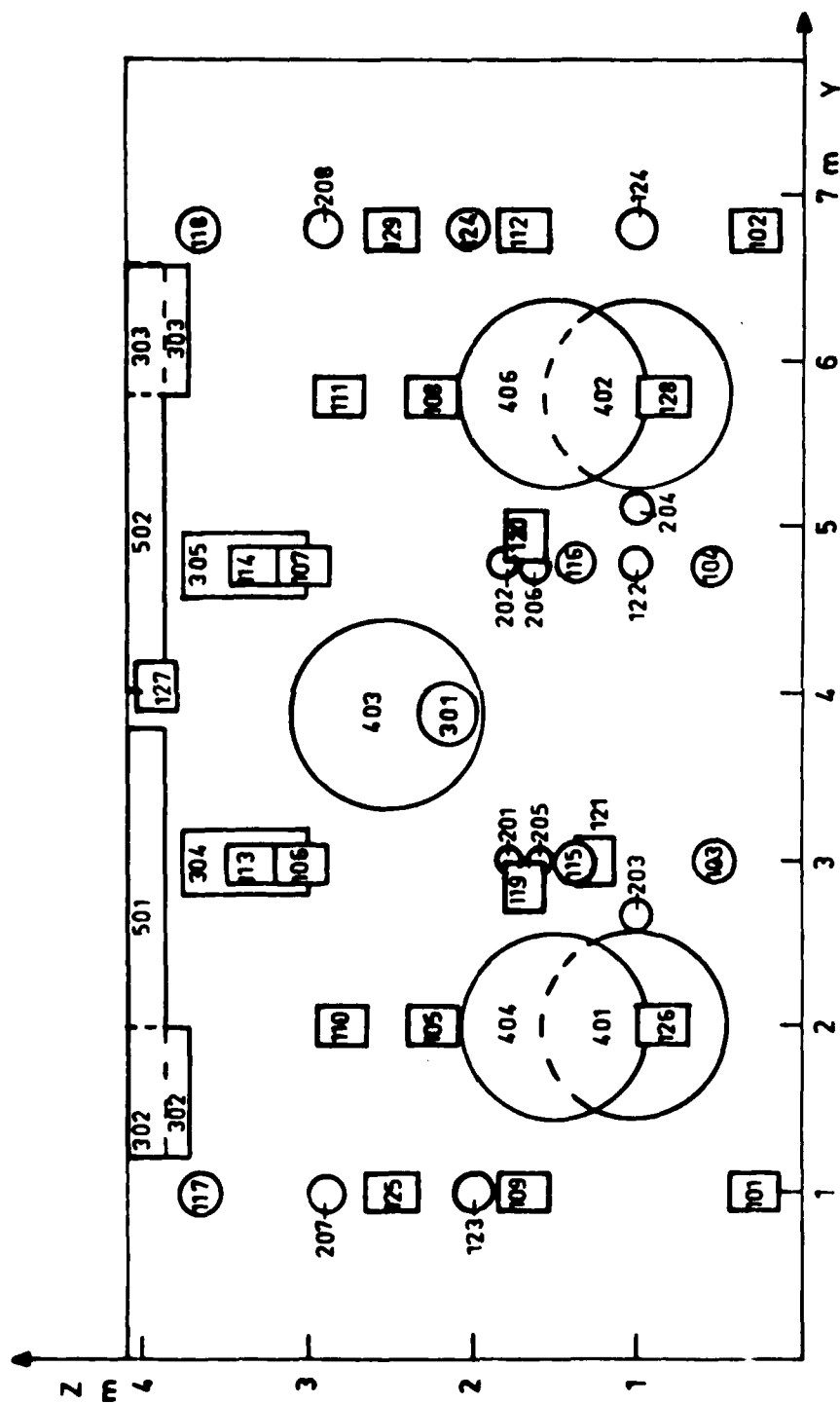
Figure 21. Engine Room from Above

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Figure 22. Engine Room from the Rear

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Table 3. Engine Room Critical Component Details

Number	Shielding in mm Dural	Coordinates for the Ends of the Axle of the Cylinder (cm)						Radius	Damage Criteria %	
		X_1	Y_1	Z_1	X_2	Y_2	Z_2			
101	5	100	100	15	100	100	45	12	87	FILTER
102	5	100	680	15	100	680	45	12	87	FILTER
103	5	100	300	55	130	300	55	12	87	FILTER
104	5	100	480	55	130	480	55	12	87	FILTER
105	5	200	200	210	200	200	240	12	87	Fuses
106	5	200	300	290	200	300	320	12	87	Hydraulic Tank
107	5	200	480	290	200	480	320	12	87	"
108	5	200	580	210	200	580	240	12	87	Fuses
109	5	300	100	155	300	100	185	12	87	FILTER
110	5	300	200	265	300	200	295	12	87	FILTER
111	5	300	580	265	300	580	295	12	87	FILTER
112	5	300	680	155	300	680	185	12	87	FILTER
113	5	300	300	340	330	300	340	12	87	FILTER
114	5	300	480	340	330	480	340	12	87	FILTER
115	5	400	300	140	430	300	140	12	87	CIRK.-TANK
116	5	400	480	140	430	480	140	12	87	CIRK.-TANK
117	5	500	100	365	530	100	365	12	87	FILTER
118	5	500	680	365	530	680	365	12	87	FILTER
119	5	500	270	170	500	300	170	12	87	FILTER
120	5	500	480	170	500	510	170	12	87	FILTER
121	5	570	300	110	570	300	140	12	87	HYDRAUL TANK
122	5	570	480	100	600	480	100	12	87	HYDRAUL TANK
123	5	600	100	200	630	100	200	12	87	FILTER
124	5	600	680	200	630	680	200	12	67	FILTER
125	5	700	100	235	700	100	265	12	87	FILTER
126	5	700	200	70	700	200	100	12	87	CIRK.-TANK
127	5	700	390	390	700	420	390	12	87	FILTER
128	5	700	580	70	700	580	100	12	87	CIRK.-TANK
129	5	700	680	235	700	680	265	12	87	FILTER
201	14	70	300	180	100	300	180	10	99	EL PUMP
202	14	70	480	180	100	480	180	10	99	EL PUMP
203	14	140	270	100	170	270	100	10	99	DIRECT PUMP
204	14	140	510	100	170	510	100	10	99	DIRECT PUMP
205	10	270	300	160	300	300	160	10	99	Lubr Pump
206	10	270	480	160	300	480	160	10	99	"
207	14	470	100	290	500	100	290	10	99	EL PUMP
208	14	470	680	290	500	680	290	10	99	EL PUMP
209	14	610	390	245	640	390	245	10	99	DIRECT PUMP
210	10	650	200	105	680	200	105	10	99	SMOPUMP
211	10	650	580	105	680	580	105	10	99	SMOPUMP
301	4	21	390	215	100	390	215	19	63	Empty CIRKTANK
302	3	100	121	390	100	200	390	19	63	CIRK.-TANK
303	3	100	580	390	100	659	390	19	63	CIRK.-TANK
304	3	700	300	300	700	300	379	19	63	Voltage Regu
305	3	700	480	300	700	480	379	19	63	"
401	12	141	200	100	274	200	100	57	54	Gear Housing
402	12	141	580	100	274	580	100	57	54	"
403	12	201	390	250	334	390	250	57	54	El Generator
404	12	334	200	150	467	200	150	57	54	TURBINE
405	12	334	390	250	467	390	250	57	54	DIESEL
406	12	334	580	150	467	580	150	57	54	Turbine
407	9	467	200	150	600	200	150	57	54	DIESEL ENGINE
408	12	467	390	250	600	390	250	57	54	
409	9	467	580	150	600	580	150	57	54	

Type	Length of Axis cm	Radius cm	Shield-ing mm AL	Damage Criteria %	Number of	Can Represent
1	30	12	5	87	29	Hydraulic and Circulation tanks
2	30	10	14	99	7	Pumps
3	30	10	10	99	4	-11-
4	79	19	4	63	5	Circulation Tank Voltage Regulator
5	133	57	12	54	7	Turbine, Diesel-Engine, El Generator
6	133	57	9	54	2	Combustion Chamber

Table 4.   Engine Room Details

6.4   RESULTS FROM EXAMPLE

This program was used, with the target description described above, for evaluating three types of warheads. The evaluation of these three warheads, A, B, and C, is given in Table 5. The results show that B is not as good as A or C. A is better against an engine room and C is better against a cabin. C also has a greater blast effect in cells. Against an attack ship C is judged to be best, while A probably is better against a big landing ship. The reason for this is: C destroys cabins and cells by blast in an attack ship and has the same effect in engine rooms as A. In a landing ship the blast from C is not big enough as the cells are bigger and A's fragment effects will probably give a better result.

Table 5.   Comparison Results

	Number of Killed Critical Components		
Warhead	Cabin (Total of 30 Comp)	Engine Room (Total of 54 Comp)	Critical Cell Volume m^3
A	10	8	10
B	6	5	7
C	All	6	35

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Appendix   A

Sensitivity Analysis of PUT (N,P)

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Sensitivity Analysis of PUT (N,P)

The functions PUT $(N,P) = 1-(1-P)^N$ describes the addition to the probability of kill which comes from one fragment zone and one critical volume. (See Sections 4.3.1 and 4.3.5.1)

The following diagrams show the influence of different parameters on PUT. Note that some scales are not linear.

Interesting intervals for the parameters are:

P =(o.,0.5) and N = (1,3000)

Figure A1 shows which combinations of parameters which give PUT = 1.

Figure A2 shows the change in PUT when P varies. For PUT= (0.1,0.9) a doubling of P makes a maximum change of 0.25, and in other intervals much less.

Figure A3 shows the change in PUT when N varies. The steeper curve in Figure A2 and A3 shows the damage when both N and P are doubled, N = P x 1000.

The Influence of the Size of the Fragment Zone on PUT

Figure A4 shows the relative error in PUT when the fragment zone is doubled (the solid angle is doubled). The probability for a fragment to hit the critical volume is then reduced by 50% while the numbers of effective fragments is doubled. The relative error:

$$d = \frac{PUT\ (N.2P)\ -PUT(2N,P)}{PUT\ (N,2P)}$$

where

$$PUT\ (N,P) = 1-(1-P)^N$$

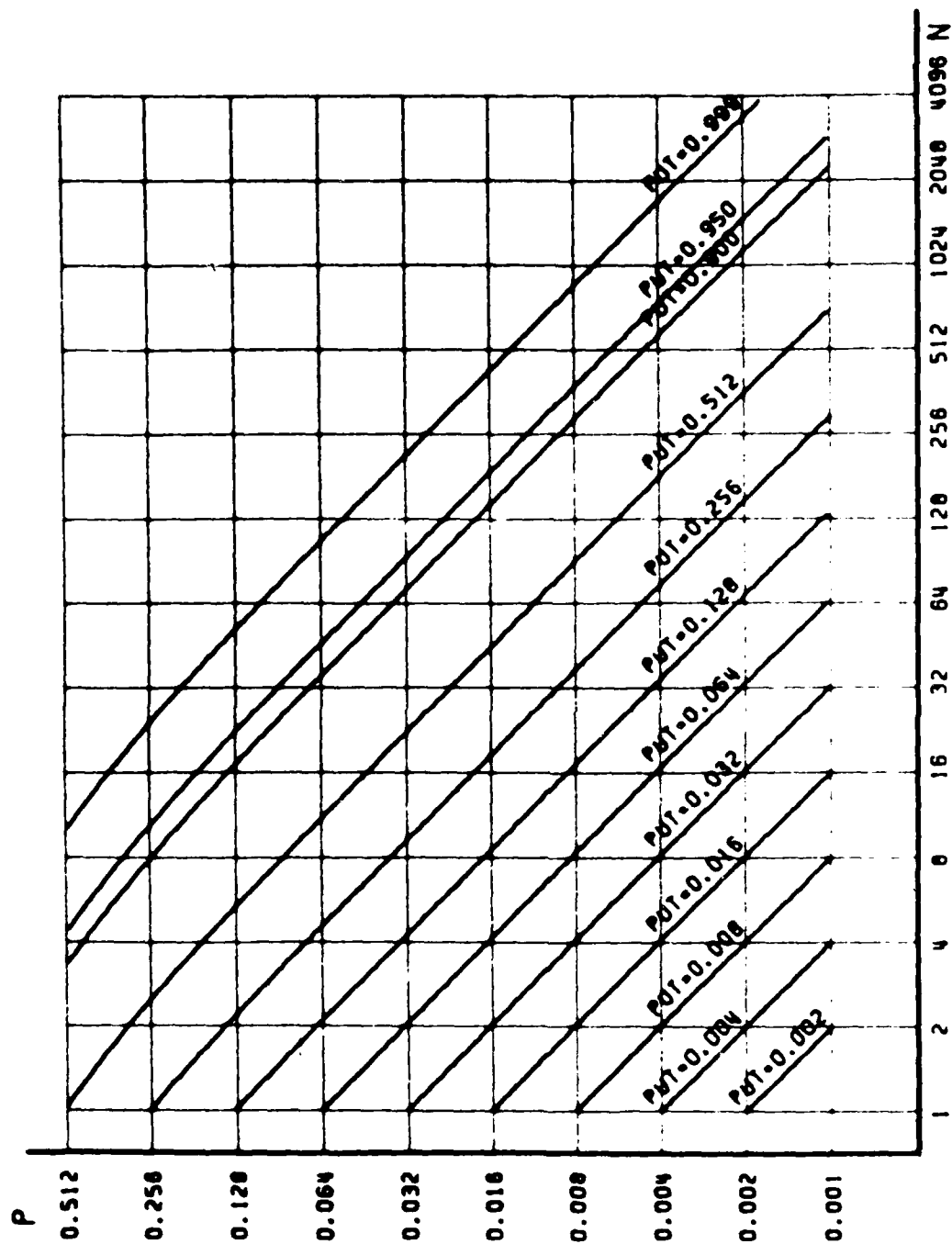The error is greatest for small N and big P but is negligible for 0<P< 0.5 and N>0.
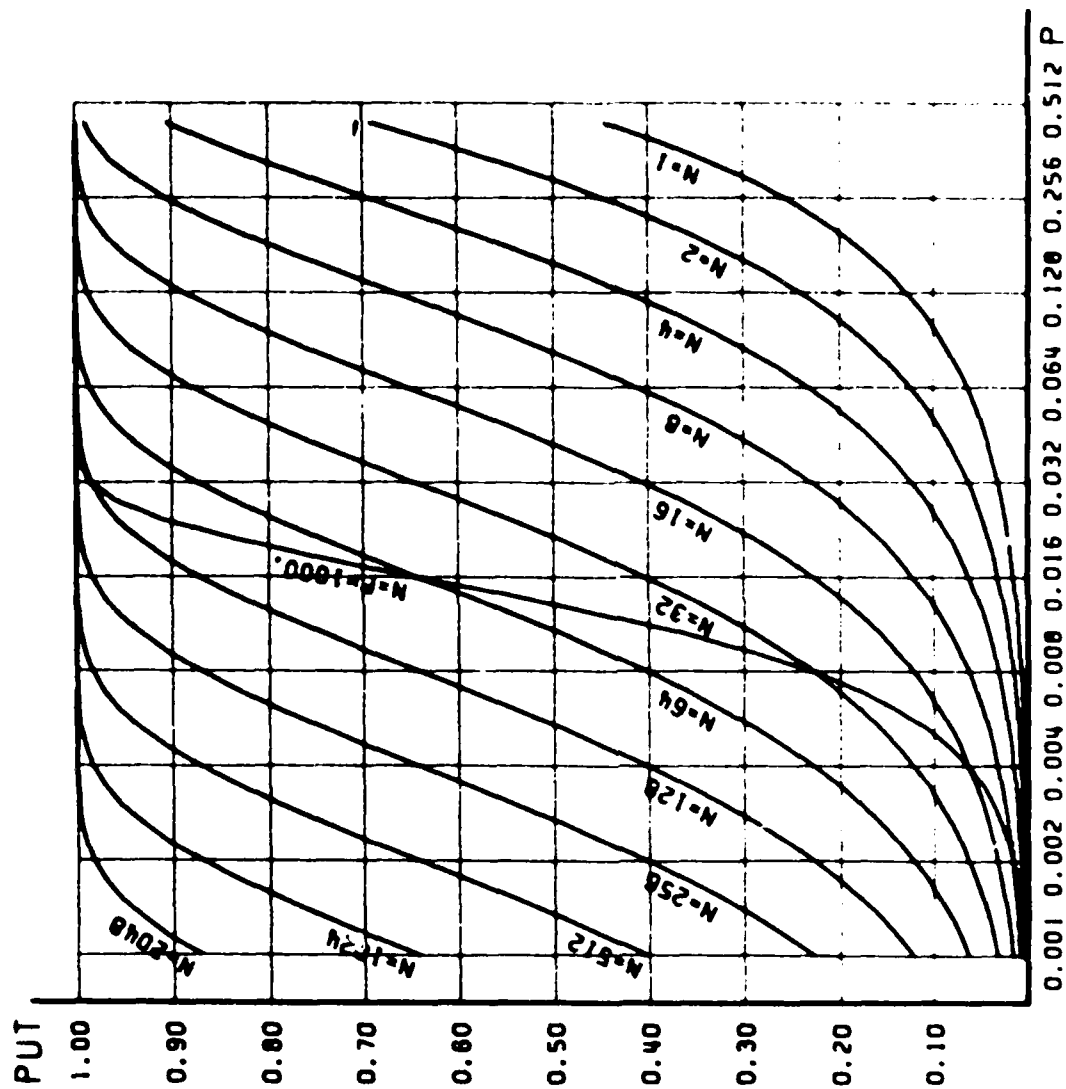
Figure A1.   PUT $(N,P) = 1 - (1-P)^N$ forGiven PUT

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Figure A2. PUT (N.P) = $1 - (1-P)^N$ for Given N
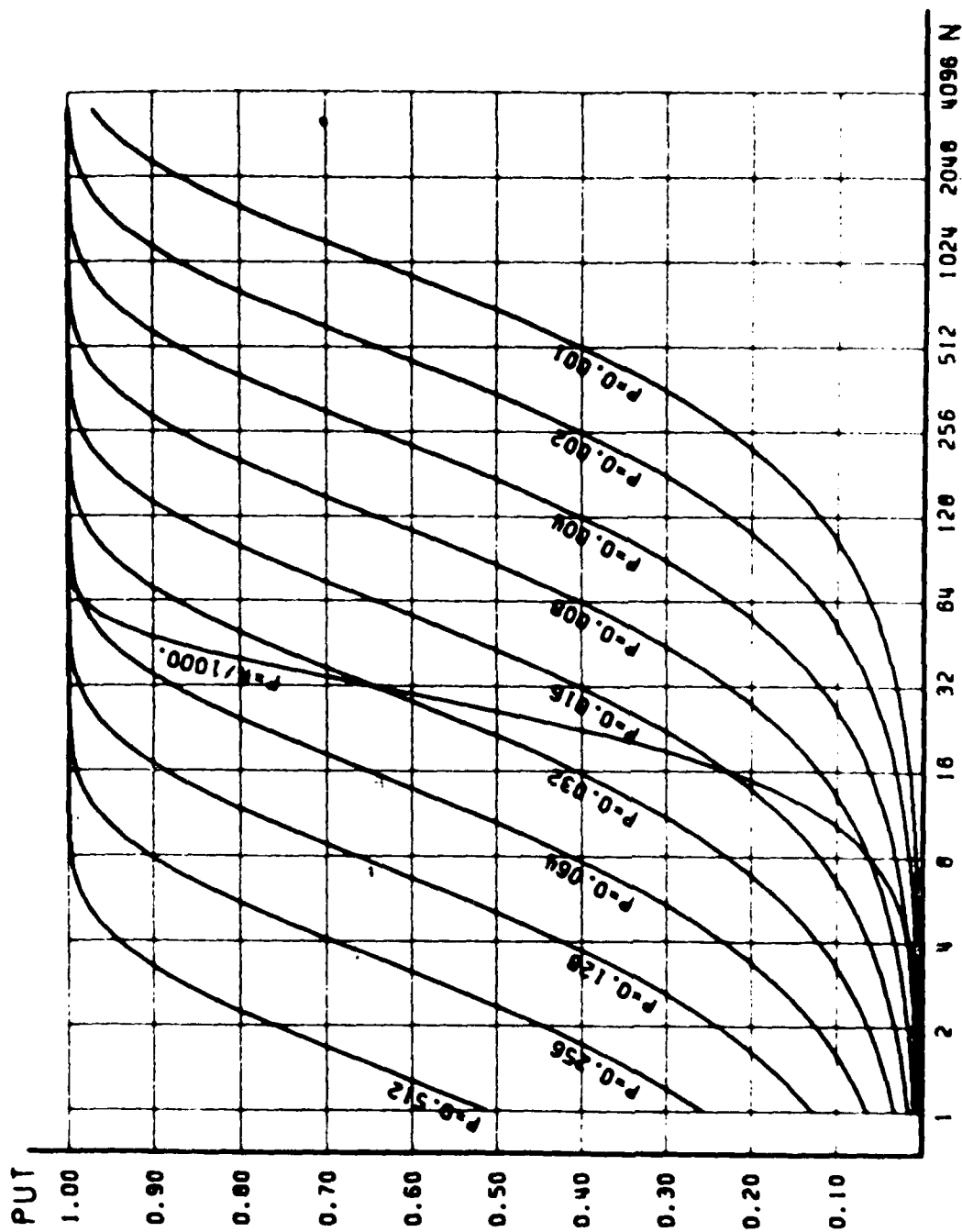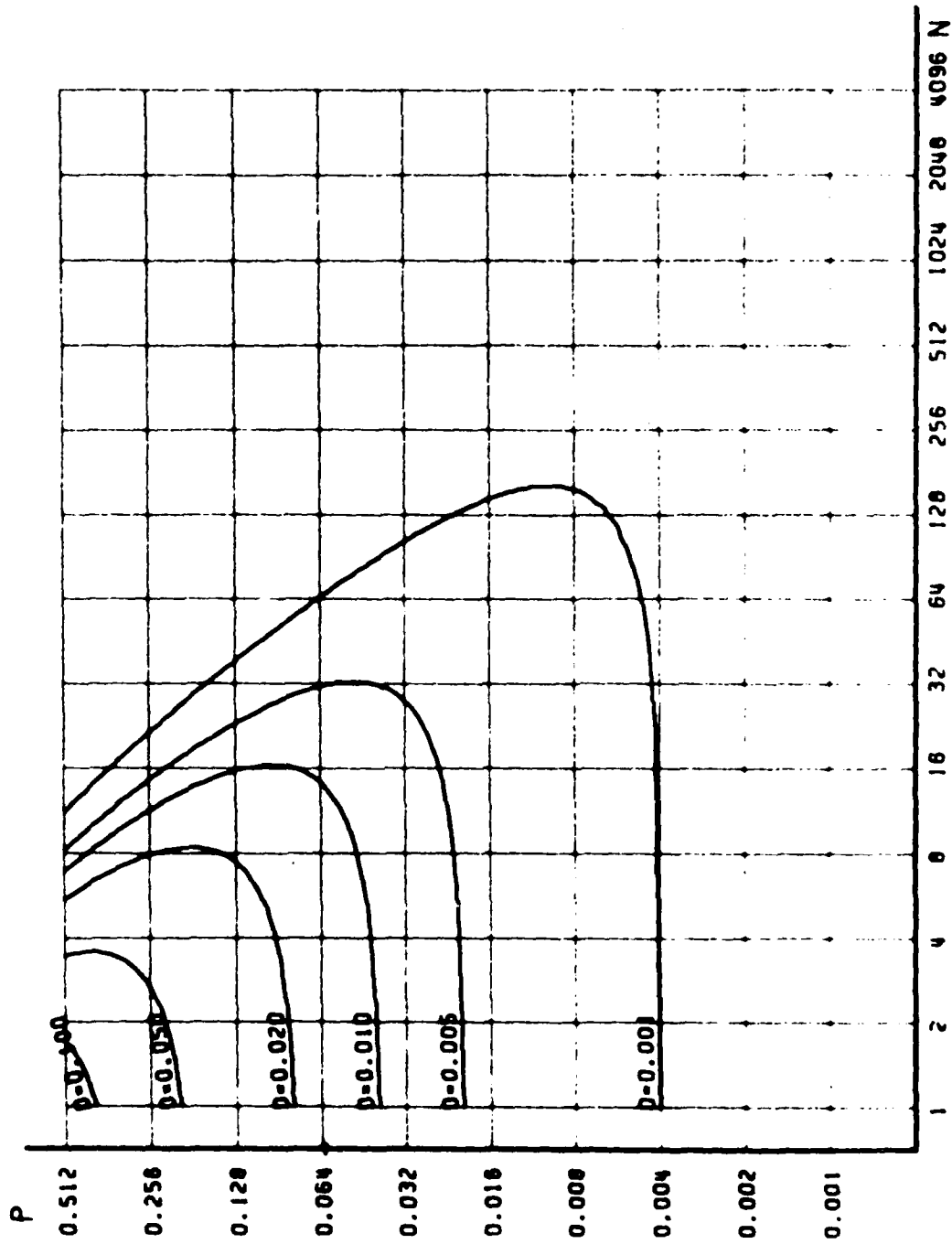
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Figure A3. PUT $(N,P) = 1 - (1-P)^N$ For Given P

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Figure A4. Relative Error $D(N,P) = (P(N,P) - PUT (2N,P/2))/PUT (N,P)$

where: $PUT(N,P) \cdot 1$ if $P \geq N$

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